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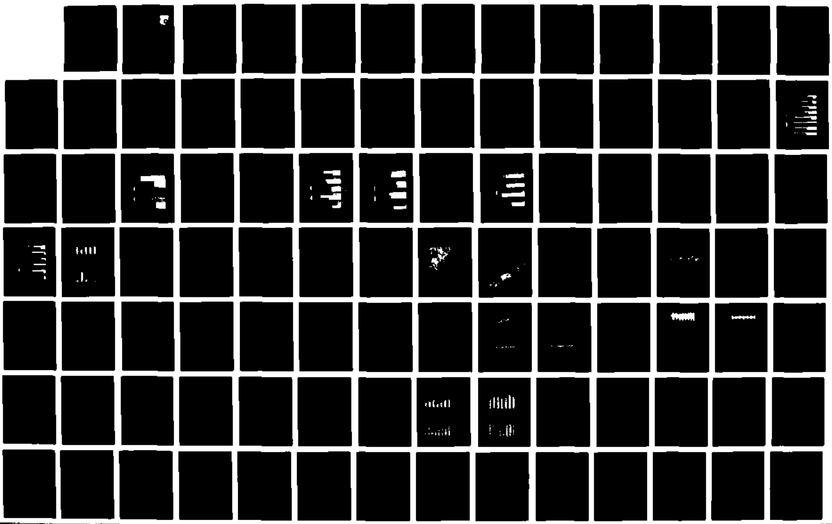

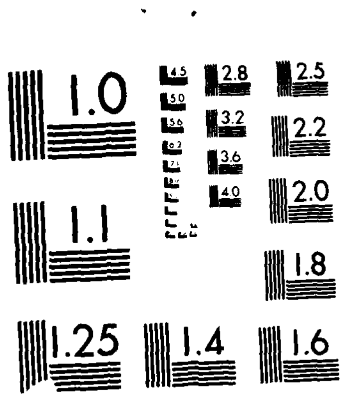

UTION TEST CHART

AFWAL-TR-88-4260

KC-135R RUMBLE INVESTIGATION

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February 27, 1989

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The KC-135R is a modified KC-135A which has had, among other things, the engines changed from the J-57 to the new F-108-CF-100 engines. Shortly after the KC-135R began SAC flight operations, a noise problem perceived as a rumbling sound in the cabin area was found in various aircraft; i.e., "Rumble." The Air Force, the aircraft manufacturer and the engine manufacturer studied the problem briefly developing a better definition of the general problem. The forcing function was determined to be the F-108 engine; however, the precise source of the noise and vibration, and the transmission path from the engine to the cabin were unknown. Keywords: aircraft engine vibration;

The University of Dayton Research Institute (UDRI) completed a review of the data available on Rumble and found that additional problem identification data was necessary before a viable engineering solution to the Rumble problem could be developed. It was the collection of the additional data required and the engineering evaluation of solutions to Rumble which was addressed during this effort.

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19. ABSTRACT

The program was divided into the following major tasks:

1) Flight and ground tests on aircraft (A/C)307.
2) Flight and ground tests of six A/C at McConnell AFB.
3) Analysis of vibration data from the F-108 and the J-57.
4) Development and evaluation of possible solutions to the Rumble problem.

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SECTION 1
INTRODUCTION AND SUMMARY

The following paragraphs present a brief introduction and summary of the program completed to resolve the Rumble problem on the KC-135R aircraft.

1.1 INTRODUCTION

The KC-135R is a modified KC-135A which has had, among other things, the engines changed from the J-57 to the new F-108-CF-100 engines. Shortly after the KC-135R began SAC flight operations, a noise problem perceived as a rumbling sound in the cabin area was found in various aircraft; i.e., "Rumble." The Air Force, the aircraft manufacturer and the engine manufacturer studied the problem briefly developing a better definition of the general problem. The forcing function was determined to be the F-108 engine; however, the precise source of the noise and vibration, and the transmission path from the engine to the cabin were unknown.

The University of Dayton Research Institute (UDRI) completed a review of the data available on Rumble and found that additional problem identification data was necessary before a viable engineering solution to the Rumble problem could be developed. It was the collection of the additional data required and the engineering evaluation of solutions to Rumble which was addressed during this effort.

This program combined the expertise of Oklahoma City Air Logistics Center (OCALC) and the University of Dayton into an effective and economical team to solve the Rumble problem. The team concept allowed the in-depth knowledge of the aircraft and technical expertise at OCALC to combine with the unique technical expertise and abilities at UDRI in such a way as to maximize the engineering capability focused on the problem. Since UDRI is an

unbiased consultant whose goals are to solve problems effectively and transition their technology to practical users, UDRI worked with a complete and open transfer of information with OCALC.

1.2 PROGRAM OBJECTIVES

The objectives of this program were:

(1) To define Rumble precisely; i.e., what were the frequencies involved and what were the sound and vibration levels during Rumble;

(2) To determine the driving force, the propagation path, and the noise/vibration radiators that were causing Rumble;

(3) To evaluate the long term effects of Rumble on both crew function and aircraft structure; and

(4) To develop and evaluate possible solutions to Rumble.

The program summary briefly describes the tasks completed to successfully complete the objectives above.

1.3 PROGRAM SUMMARY

The program was divided into the following major tasks:

(1) Flight and ground tests on aircraft (A/C) 307.

(2) Flight and ground tests of six A/C at McConnell AFB.

(3) Analysis of vibration data from the F-108 and the J-57.

(4) Development and evaluation of possible solutions to the Rumble problem.

The total effort included approximately 30 hours of flight test data collection, 8 hours of engine ground run data collection, and 45 hours of ground test data collection for model

analysis. All of this data plus the data available from the Boeing test effort, G.E. engine test data, Air Force engine acceptance vibration data, and many interviews with Air Force flight crews formed the complete data base on which analysis was completed, and the conclusions and recommendations drawn.

The major objective for the test effort on A/C 307 was to define Rumble and the area of the fuselage which was most active during Rumble. Three test flights, an engine ground run, and a modal analysis, were conducted. For complete details on the testing of A/C 307, see Section 4.

During the first flight on A/C 307 acoustic data were collected in the cabin and cargo areas of the fuselage. The first flight data indicated that the Rumble was most prominent in the cabin area. On the second flight, detailed acoustic data collected in the cabin area indicated that the maximum response occurred near the navigator's instrument panel and around the pilot's station. On the third flight vibration data were collected in the locations where high acoustic response had been measured and in locations where structural problems might be anticipated. The vibration and acoustic data from all three flights showed that the principal Rumble frequency was approximately 55 Hertz and that the overall response levels were about equal in or out of Rumble. The modal analysis of A/C 307 revealed several resonant frequencies in the 18- to 60-Hertz range.

The flight data, the ground test data, and the modal analysis data from A/C 307 all supported the hypothesis that engine imbalance forces were exciting a 55-Hz resonance in the engine aircraft structural system which caused Rumble. However, the frequency of Rumble during the Boeing test was 30 Hertz. The difference in frequency led to the McConnell flight test effort.

The primary objective of the flight test at McConnell was to establish a data base of Rumble information from multiple

aircraft. A total of six aircraft were tested and ground run data was collected on four F-108 engines. All six aircraft were able to be flown in Rumble during various portions of the flight plan. For complete details on the McConnell flight and ground test effort, see Section 5.

The principle finding from the McConnell flight test effort was that the Rumble resonant frequency varied from aircraft to aircraft and that it also varied during flight on a given aircraft. The frequency band over which Rumble occurred was 30 to 70 Hertz; however, the predominate frequencies were between 50 and 60 Hertz. The engine ground run data showed vibration responses peaking in the same 30- to 70-Hertz range as was seen in flight.

Although the frequency of the Rumble varied, the one unchanging characteristic of Rumble found in the McConnell flight tests was the beating phenomena; i.e., the peak and fade cycle in the time data. This characteristic is defined by the air crew as "Whaa, Whaa." In all of the tests the Rumble was identified by the crew when the beating phenomena was present in the dynamic data.

The objective of the study of the F-108 and J-57 vibration data was to determine:

(1) what were the specific vibration specifications for each engine and how did the specifications compare;

(2) what was the operating RPM range for each engine;

(3) what were the specific vibrational characteristics of the F-108; and

(4) if there was a common link between the acceptance run vibration data and the F-108 engines which had caused Rumble.

For complete details on the study of the F-108 and J-57 vibration data, see Section 6.

The vibration specification data was obtained from OCALC. Both engines were allowed a maximum of 0.004 inch displacement at the one per revolution frequency over the operational speed of the engine.

Vibrational data on the F-108 were obtained from CFMI. The F-108 engine has overall engine vibration resonance in the 40- to 75-Hertz range and the speed range of the low speed spool was approximately 20 to 80 Hertz (1200 to 4800 RPM).

One hundred and seventeen sets of engine acceptance vibration data were reviewed. Of the engines reviewed, 15 had been identified in the field as Rumble engines. Some trends were established from the engine acceptance data on the engines which caused Rumble; however, due to the low number of data sets available, no conclusions were drawn.

The final effort conducted on this program was the development and evaluation of solutions to the Rumble problem. For complete details on this particular effort, see Section 7. The design effort concentrated on the three principal structural components involved in Rumble, i.e., the engine, the nacelle/wing, and the fuselage.

The possible solutions for each component were:

1. Engine

    - Reduce the acceptance level vibration specification thereby reducing the force driving Rumble.
    - Redesign the engine static structure which would reduce the resonant amplification which currently existed and therefore reduce the driving forces.
    - Change engine RPM to change frequency of driving force thereby reducing resonant amplification.

2. Nacelle/wing

- Add damping to reduce resonant amplification and reduce the Rumble driving force.
- Redesign the structure to change resonant frequencies which would reduce resonant amplification.

3. Fuselage

- Redesign the structure to change resonances which would reduce resonant amplification.
- Add damping and acoustic treatment to reduce vibration and noise in the cabin area.

All of the above design/system changes were analyzed. Apparently the only feasible solution is to change the engine speed.

2.0 CONCLUSIONS

The following conclusions were reached as a result of the data collected and analyzed during this project.

(1) Rumble is the beating of several frequencies in the 30- to 70-Hertz range which results in the peak and fade time history which aircraft crew members describe as a "Whaa, Whaa" sound.

(2) Rumble is caused by the complex coupling of the F-108 rotor imbalance forces and the structural dynamic characteristics of the engine, nacelle, and aircraft systems. Figure 1 illustrates the frequency range of each of the contributors to Rumble. When the frequencies of the contributors coincide, Rumble occurs.

(3) Because of the complexity of the total structural system, Rumble is not a single dynamic response phenomena. In other words, the precise transmission path, resonant structure, and vibration/acoustic resonators vary from aircraft to aircraft and Rumble event to Rumble event.

(4) The overall noise level during Rumble is 1 to 3 dB higher than during standard flight, while the vibration level was a maximum of 9 times higher during Rumble.

(5) The noise and vibration levels encountered during flight tests were of a level that no long term structural failure problems would be anticipated and that no crew functions would be inhibited.

(6) The tonal quality of the background noise during a standard flight is similar to white noise which most people find relaxing; however, the beating or "Whaa, Whaa" tones during Rumble are more readily detectable by people even at lower sound levels and are generally

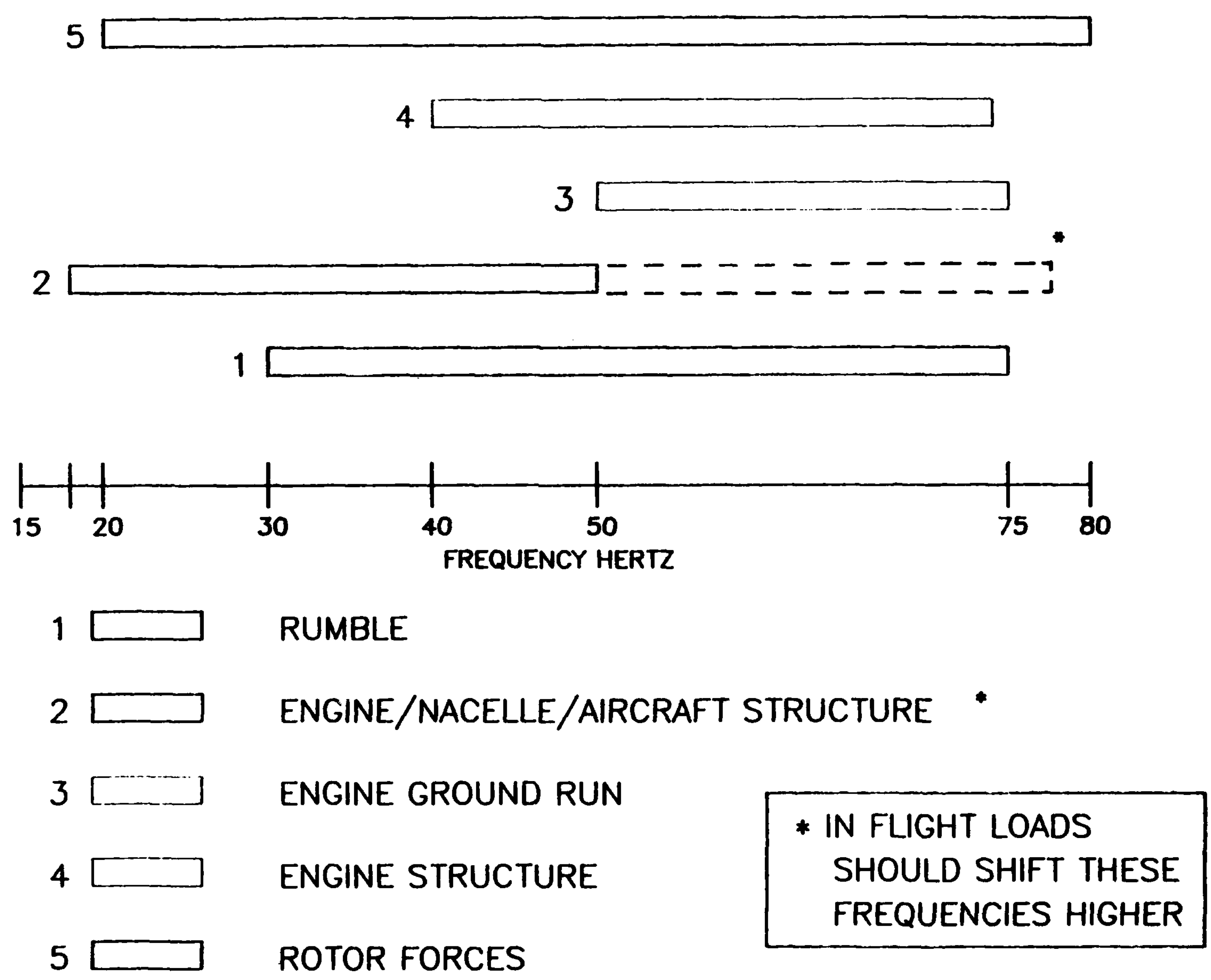


Figure 1. Comparison of the Frequency Range Covered by the Contributors to Rumble.

considered annoying. It is the tonal change between non-Rumble and Rumble that the crew detects not an increase in sound pressure.

(7) The only reasonable solution to the Rumble problem is to change the engine speed which takes the structural systems out of resonance and stops the Rumble.

(8) There appears to be a relationship between engine acceptance run vibration response and the incidence of Rumble on an aircraft.

(9) The predominate engine positions which generate Rumble are Positions 2 and 3.

(10) Engine Positions 1 and 4 can produce Rumble-like dynamic responses which can be measured by dynamic instrumentation but generally not detected by the aircraft crew.

(11) The J-57 engine could not have excited a similar Rumble phenomenon in the A models because the J-57 operates at too high a rotational speed.

3.0 RECOMMENDATIONS

The following recommendations are made based on the results of the effort completed:

(1) The recommended solution for a Rumble incident in flight is to change the speed of the engine causing the Rumble.

(2) It is suggested that the higher acceptance run vibration engines be placed in Positions 1 and 4.

(3) If a Rumble cannot be stopped by changing engine speed, the engine balance should be checked and the engine replaced if out of balance.

(4) If Rumble is accompanied by excessive vibration in the engine controls, the engine balance should be checked and the engine replaced if out of balance.

(5) From the limited data available, the majority of the engines which Rumble had a vibration response about 0.003 inch at the turbine transducer location. It is recommended that a more detailed comparison of the acceptance run vibration data and engine which Rumble be completed. If this trend is proven correct, Rumble could be reduced significantly by reducing the vibration specification for the engine. The ramification of reducing the vibration specifications would have to be defined if it were decided to stop Rumble by lowering the engine vibration specifications.

(6) No structural modification effort or damping effort is recommended as a solution to the Rumble problem.

(7) It should be noted that on all aircraft evaluated the Rumble level was identified by the crew as typical. The level of this vibration was determined to be small and should have no impact on the crew or the aircraft.

If a vibration or noise occurs which has the characteristics of Rumble but is noticeably higher in amplitude than the typical Rumble, it should not be ignored. All the recommendations are for the typical Rumble.

4.0 DETAIL ACOUSTIC AND VIBRATION STUDY ON A/C 307

The first step in this program was to define the Rumble problem. The following section details the efforts and results of a flight test on Aircraft Number 307 and a modal analysis test of the engine/nacelle/wing structure.

4.1 FLIGHT TESTS ON A/C 307

During the flight test, three data gathering flights and one ground engine run test were conducted. Both acoustic and vibration data were collected under Rumble and no-Rumble conditions. The data collection and analysis were completed using a Gen Rad 2510 Micro-Modal Analyzer.

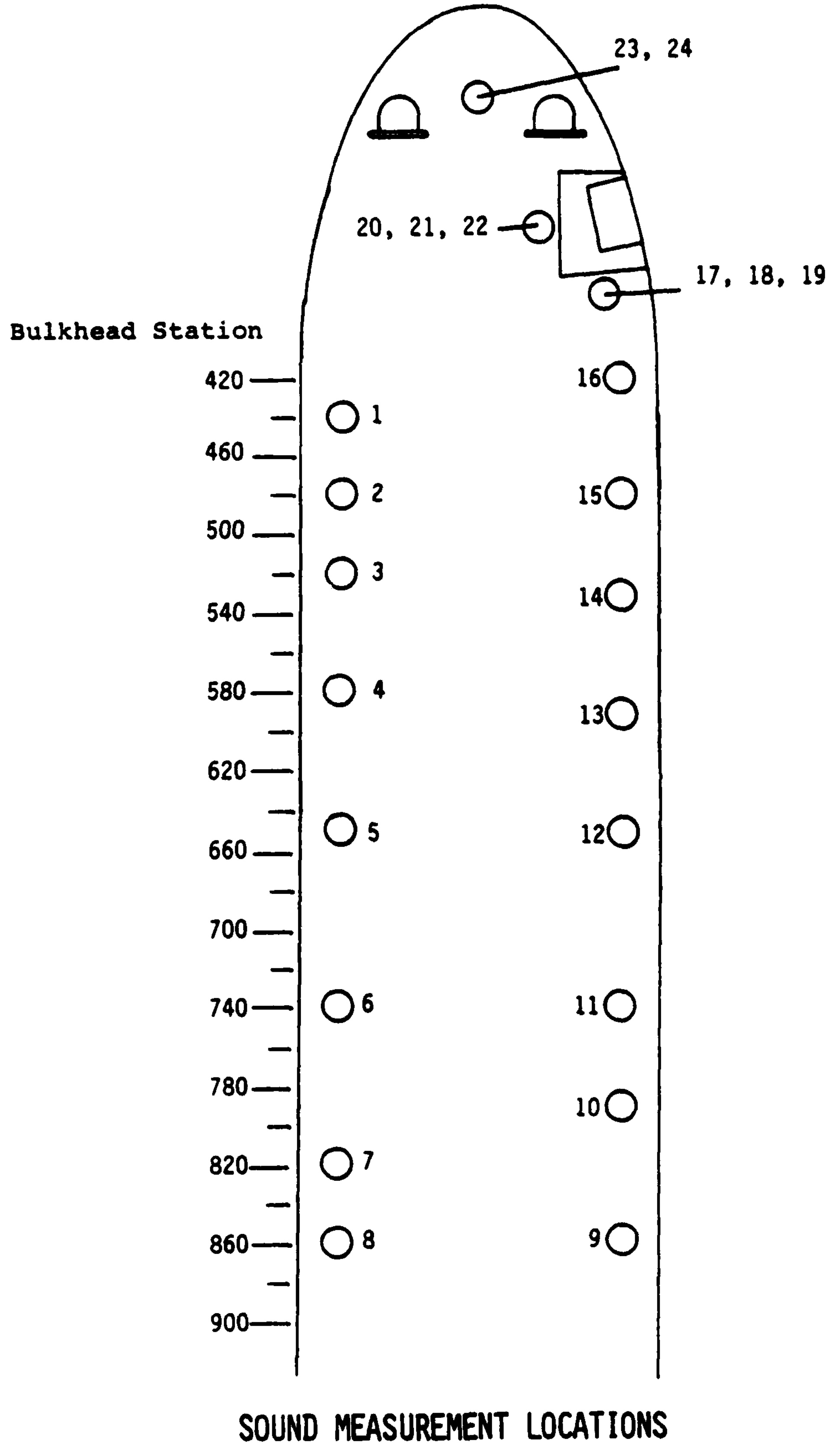
4.1.1 Flight 1

The objective of the first flight was to establish the basic characteristic of Rumble and to determine the aircraft locations where Rumble was predominant on A/C 307. Based on work by BMAC done on another aircraft where the Rumble was identified in the 30-Hertz frequency range, it was decided to collect data from 0 to 100 Hertz to establish the frequency content of Rumble on A/C 307.

Figure 2 illustrates the positions of the 24 test points evaluated during Flight 1. Table 1 details the exact location of each test point on the aircraft. The data collected was acoustic intensity and sound pressure versus frequency. Figure 3 presents a typical sound pressure plot from the cargo bay area.

Figure 4 summarizes the data collected along the left side of the cargo bay. There was some variation in the data as we progressed along the fuselage. The variation of the sound pressure in the cargo bay was insignificant when we consider the facts that each measurement was taken at a different time, which

FIRST FLIGHT



SOUND MEASUREMENT LOCATIONS

Figure 2. Measurement Locations for First Flight.

TABLE 1

SOUND DATA (FIRST FLIGHT)

Pt	Station
1	LS 440
2	LS 480
3	LS 520
4	LS 580
5	LS 650
6	LS 740
7	LS 820
8	LS 860
9	RS 860
10	RS 720
11	RS 740
12	RS 650
13	RS 590
14	RS 530
15	RS 480
16	RS 420
18	RS 393 M
19	RS 393 B
20	RS 300 T
21	RS 300 M
22	RS 300 B
23	C 260 T
24	C 260 M

NOTE: RS - Right Side 3 feet above floor
LS - Left Side 3 feet above floor
M - 3 feet above floor
B - 1 foot above floor
T - 6 feet above floor
C - Between pilot and co-pilot seat

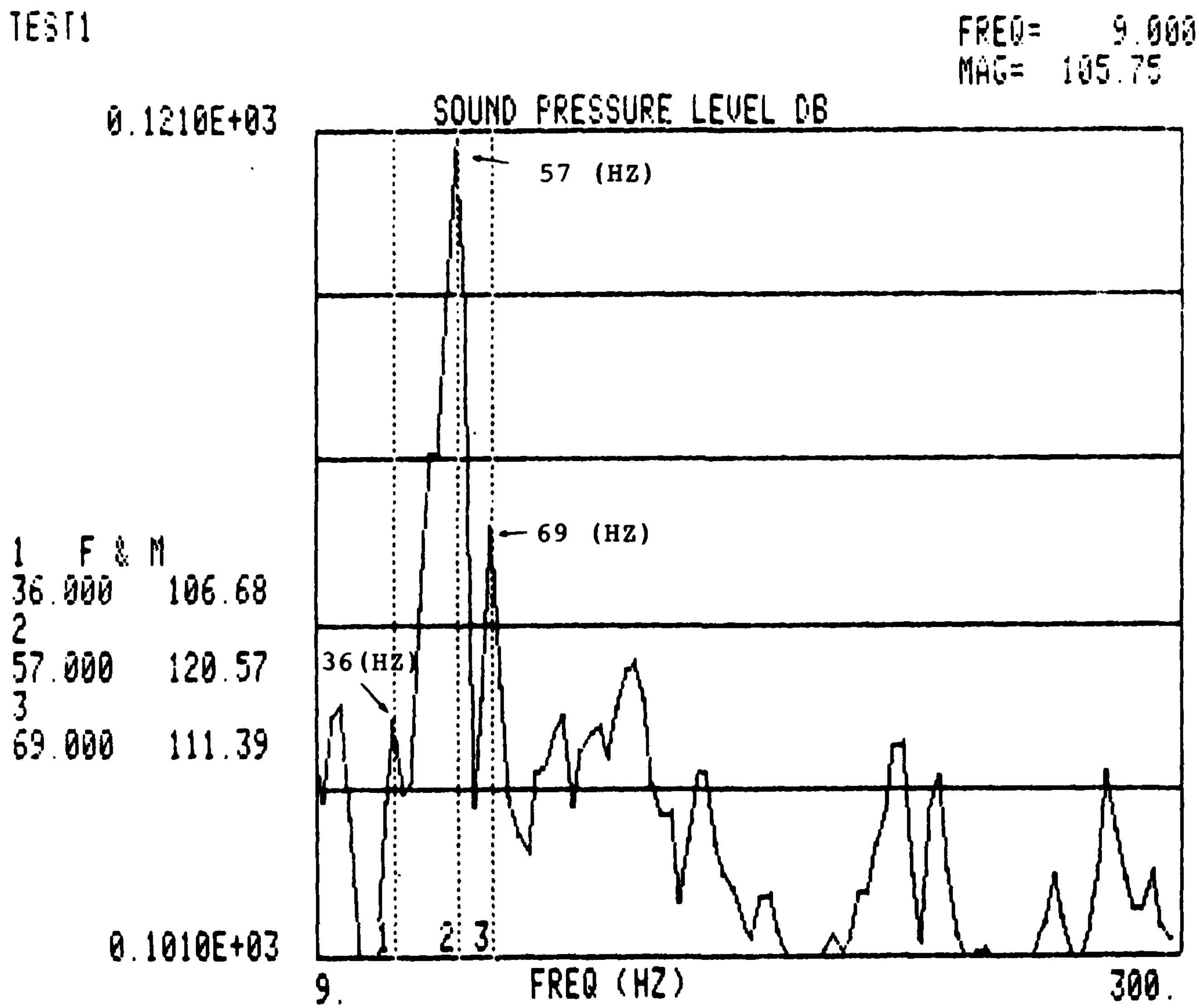


Figure 3. Typical Sound Pressure Plot From Cargo Bay Area.

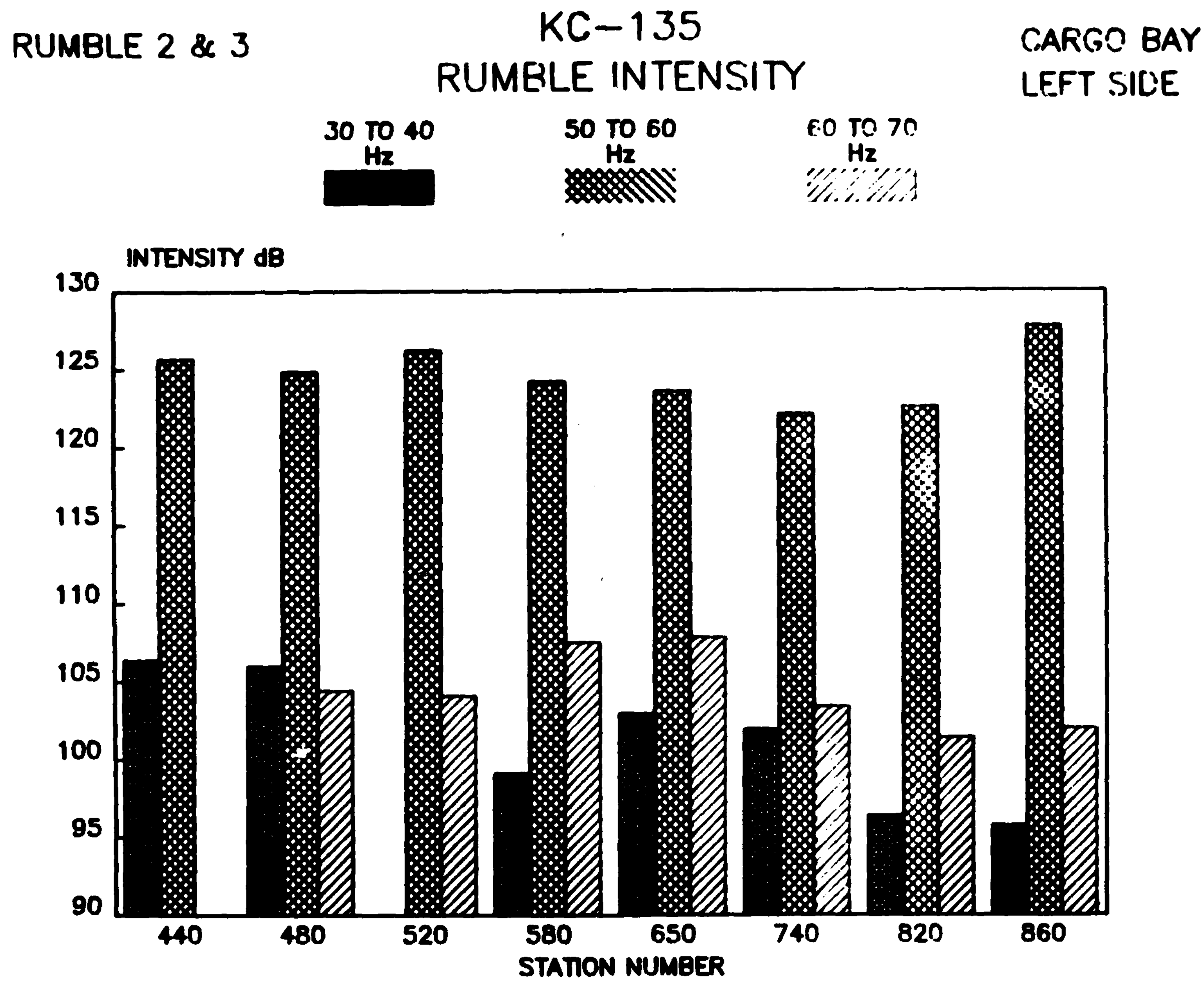


Figure 4. Acoustic Intensity Measurements Data from the Left Side of the Cargo Bay with Engines 2 and 3 Rumbling.

would cause variations since the Rumble level was not time-invariant, and that a 1- to 3- dB experimental variation was typical in these types of measurements. The fact that no strong Rumble radiator was identified in the cargo bay i.e., no single area where the Rumble was coming from, indicated that to effectively reduce the Rumble in the cargo bay would require acoustically treating the entire cargo bay.

Figure 5 is the sound pressure data from point 18 in the cockpit area. Figure 6 compares the peak values from the data in Figures 3 and 5. As shown, the cockpit area had higher levels in Rumble than the cargo bay.

Based on a quick review of the Flight 1 data immediately after the flight and the fact that Rumble was a crew-related problem, the decision was made to concentrate on the cockpit area during Flight 2.

Data for all 24 points evaluated on Flight 1 are given in Appendix A.

4.1.2 Flight 2

The objective of Flight 2 was to detail the characteristics of Rumble in the cockpit area. This objective was accomplished through the collection of sound pressure and sound intensity data at the locations shown in Figure 7. Table 2 lists the flight conditions under which data were collected for each of the measurement locations.

The data collected on Flight 2 demonstrated the same basic characteristics as the data collected during Flight 1. Figure 8 presents a summary of the data from position 4 for various flight conditions. The three active frequency ranges were 30 Hertz to 40 Hertz, 50 Hertz to 60 Hertz, and 60 Hertz to 70 Hertz. As shown in Figure 8, the Rumble was considered active when the 50-Hertz to 60-Hertz frequency had a high response. Figure 9 presents a summary of the data collected for various

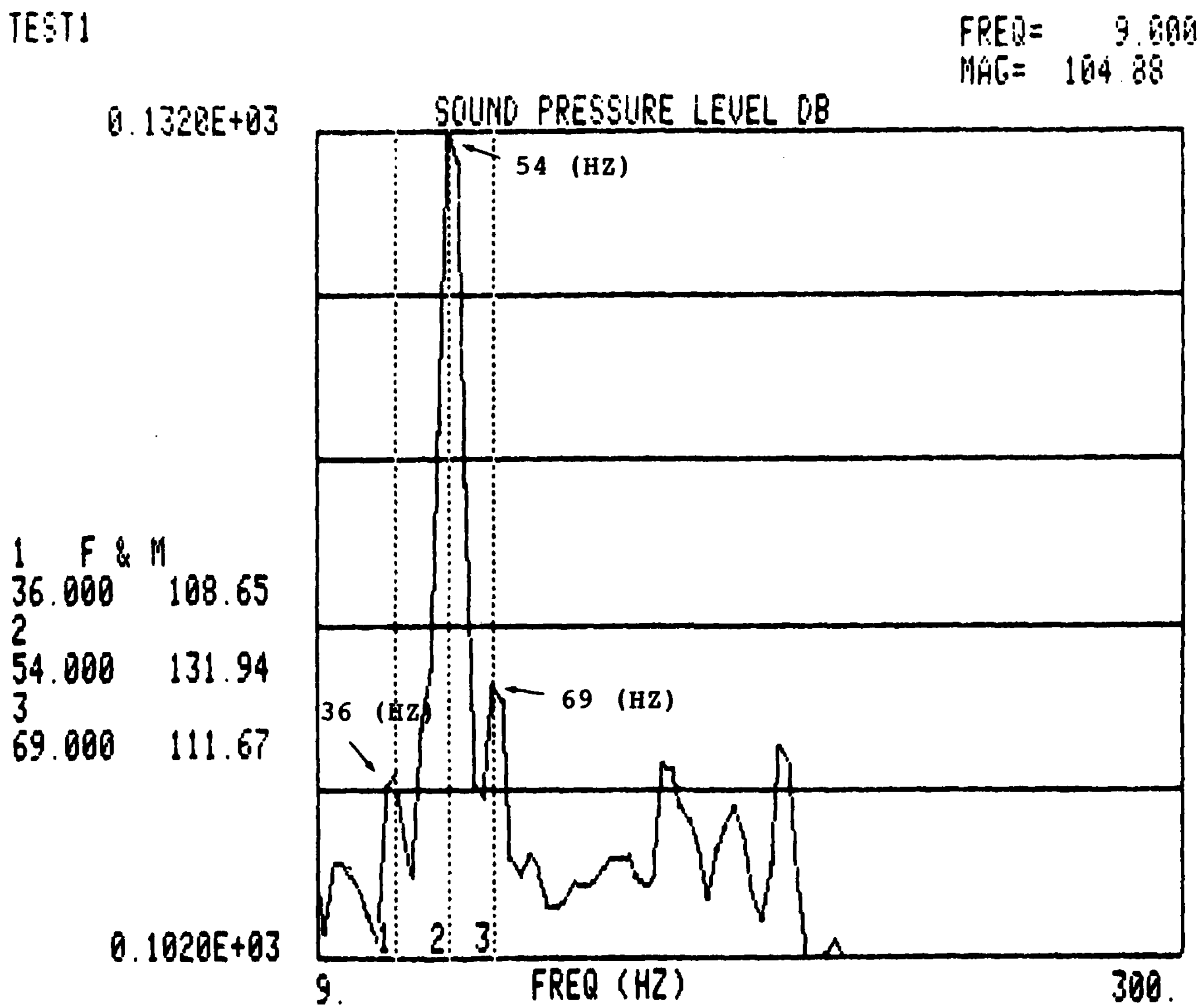


Figure 5. Frequency Spectrum of the Sound Pressure For Point 18 in the Cockpit Area.

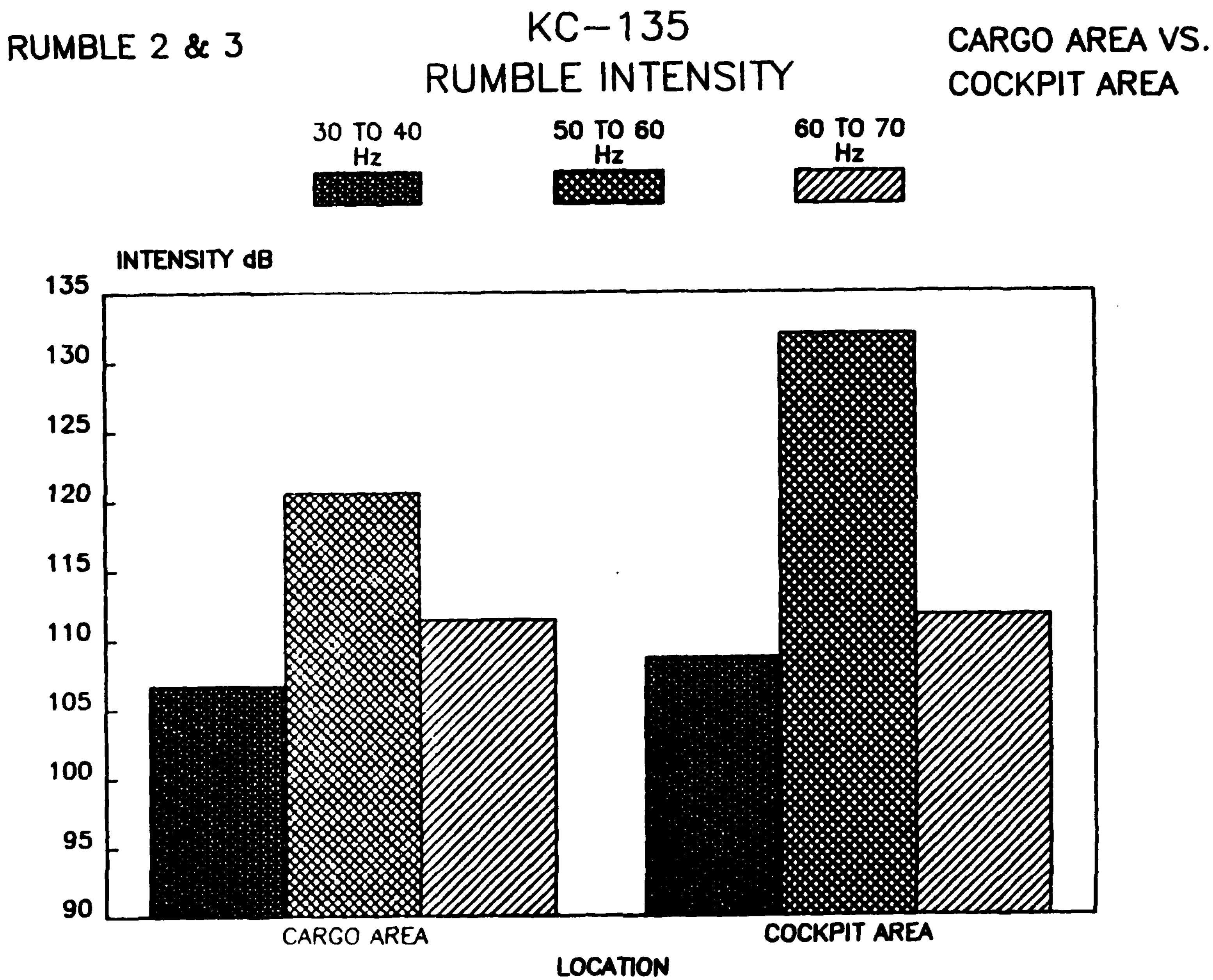
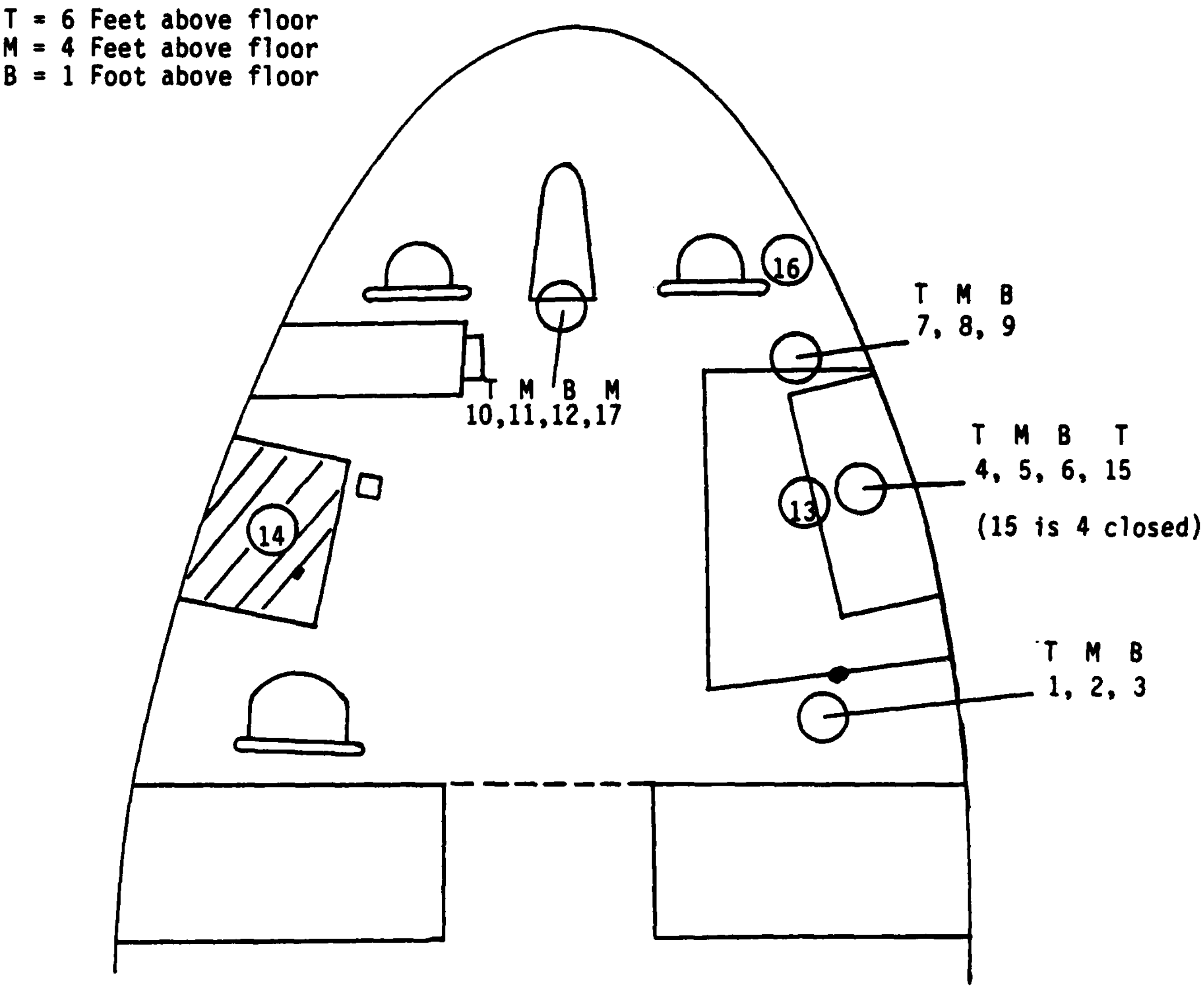


Figure 6. Comparison of Typical Data from the Cargo Bay and the Cockpit Area During Rumble.

SECOND FLIGHT



SOUND MEASUREMENT LOCATIONS

Figure 7. Measurement Locations for Second Flight.

TABLE 2

LOCATIONS AND FLIGHT CONDITIONS FOR MEASUREMENTS ON SECOND FLIGHT

Pt	Flight Condition						
	No Rumble	Rumble 2	Rumble 3	Rumble 2 & 3	Rumble 2 & 3 Right Turn	Rumble 1, 2, 3 & 4
1				x		
2				x		
3				x		
4	x	x	x	x	x	x
5	x	x	x	x		
6	x	x	x	x		
7				x		
8				x		
9				x		
10	x	x	x	x		
11	x	x	x	x		
12	x	x	x	x		
13				x		
14				x		
15				x		
16				x		
17	x	x	x	x		x

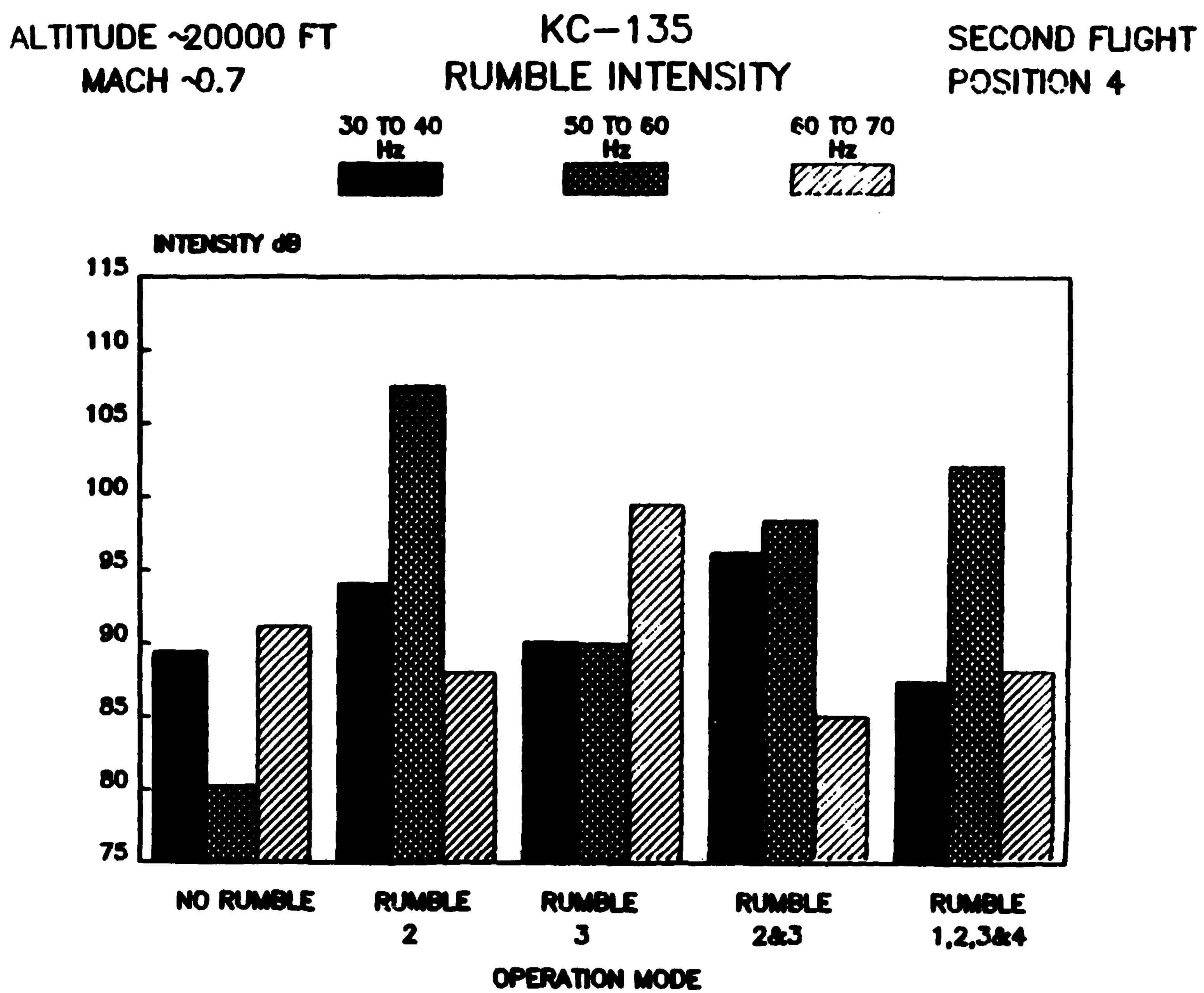


Figure 8. Second Flight Data for Point 4.

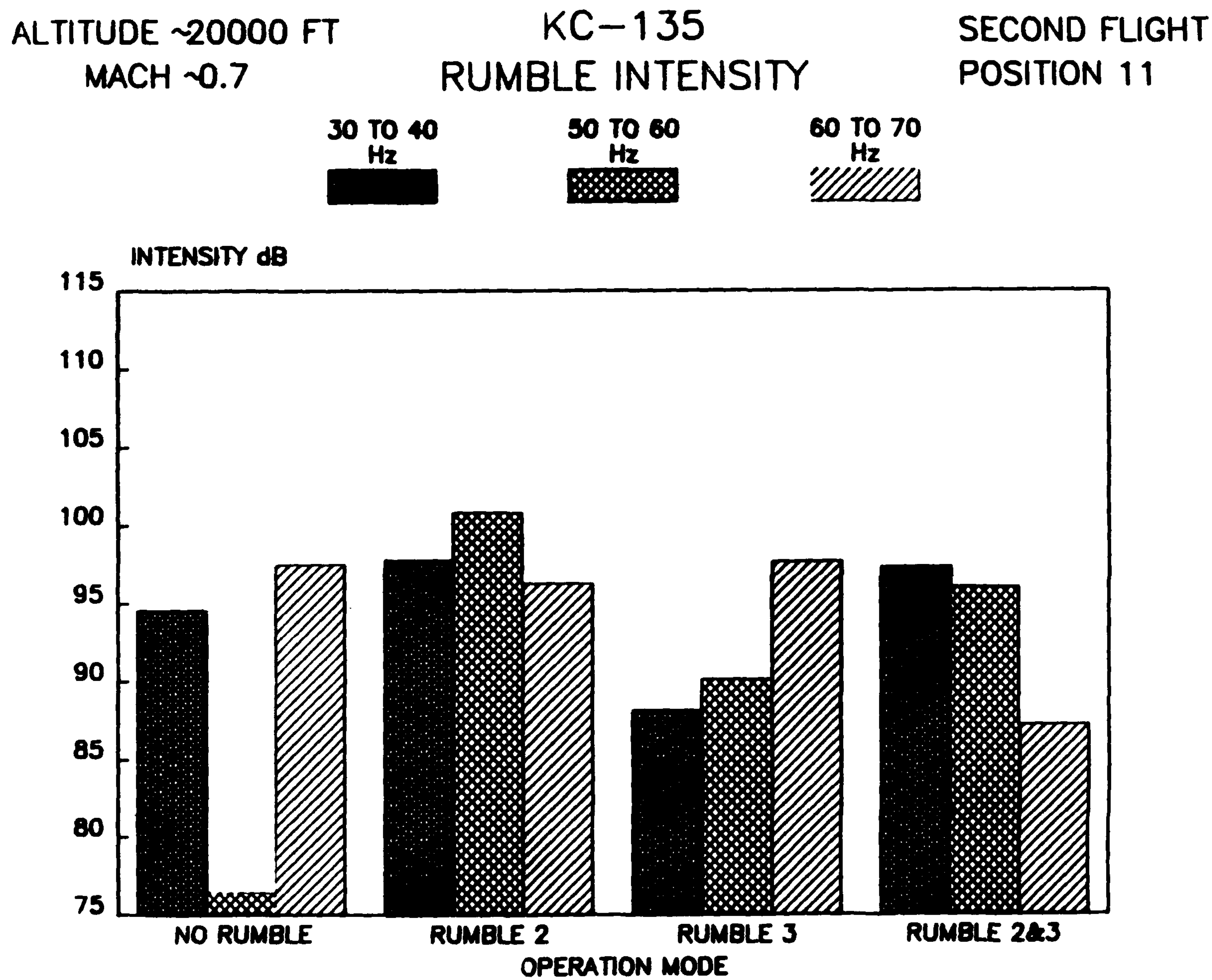


Figure 9. Position 11, Second Flight Data.

flight conditions at position 11. These data support the trends indicated in Figure 8.

Figure 10 presents the data for the 50-Hz to 60-Hz range taken at position 4 both A weighted and no weighting. The A weight filter represents the sensitivity of the normal ear. As seen in Figure 10, the amplitudes of the low frequencies peaks associated with Rumble are significantly reduced by A weighting; however, the overall broadband sound pressure level was not reduced by A weighting. The ear senses the onset of the Rumble by the tonal quality change in the noise environment, not by an increase in pressure. The human body is sensitive to the Rumble vibration level at low frequencies (see Figure 11). UDRI believes that the sensing of the vibration was most likely the method used by the flight crews to detect Rumble.

The complete set of data collected during Flight 2 is contained in Appendix B.

A quick review of the data collected during Flight 2 resulted in the conclusion that sufficient acoustic data had been collected and that the next set of data to be acquired should be vibration data. Flight 3 was scheduled for vibration data collection.

4.1.3 Flight 3

The objective of Flight 3 was to define the vibration response of the aircraft structure in the cockpit and cargo bay areas during various flight conditions. This objective was accomplished through the collection of the vibration data at the locations shown in Figure 12 under the flight conditions shown in Table 3. The vibration data were collected, analyzed and then stored as power spectrums. A typical spectrum is shown in Figure 13.

The vibration data collected in Flight 3 support the acoustic data collected in Flights 1 and 2. As shown in

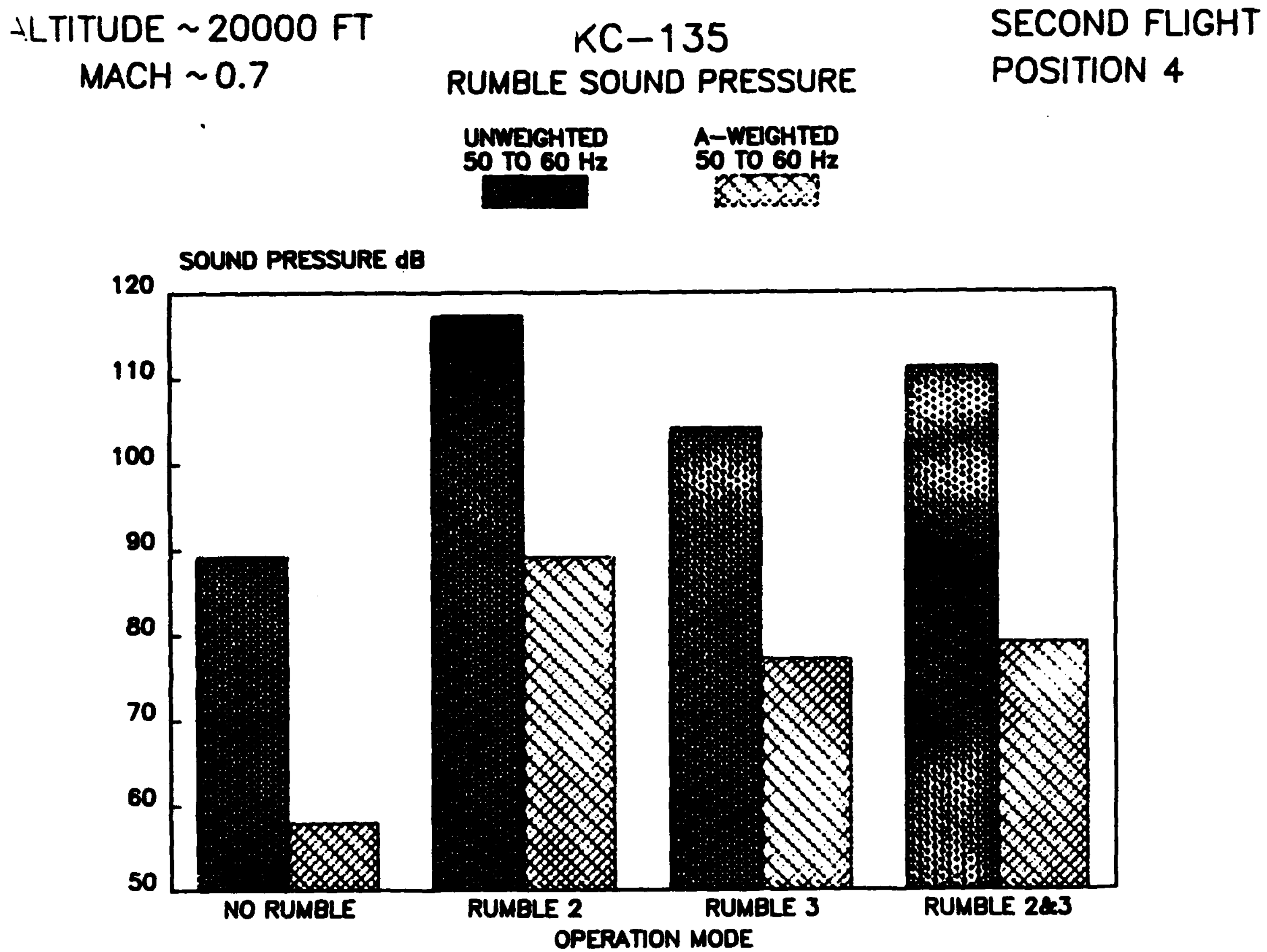


Figure 10. A- Weighted VS No Weighting for Position 4, Second Flight.

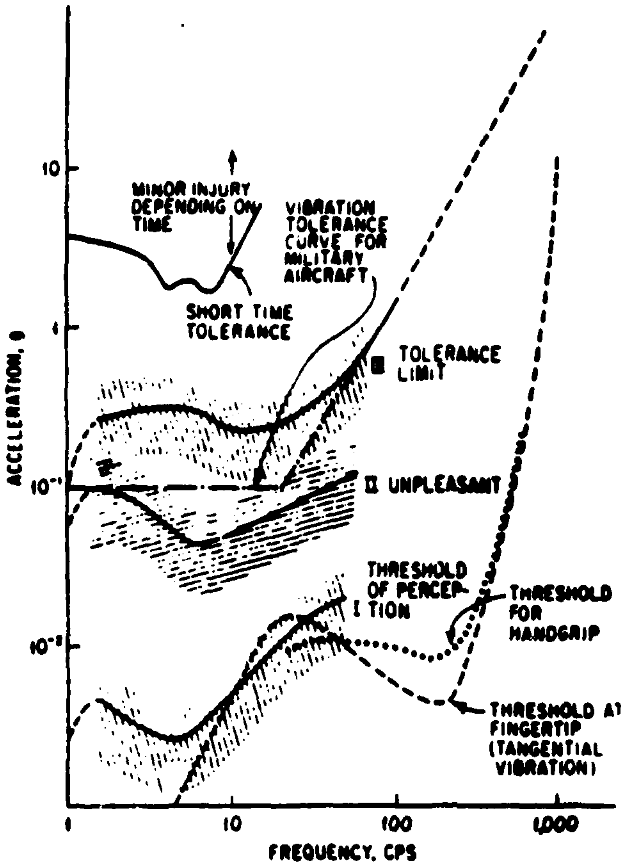


Figure 11. Vibration Tolerance Criteria. Peak acclerations at which subjects preceive vibrations (I); find it unpleasant (II); or refuse to tolerate it further (III). The shaded areas are one standard deviation on either side of the mean. These curves are for subjects without any protection, exposure time 5 to 20 min. The short-time tolerance curve is for subjects with standard Air Force lab belt and shoulder harness, exposure time approximately 1 min. The WADD "Vibration Tolerance Curve For Military Aircraft" is used for long-time exposure in military aircraft.

THIRD FLIGHT

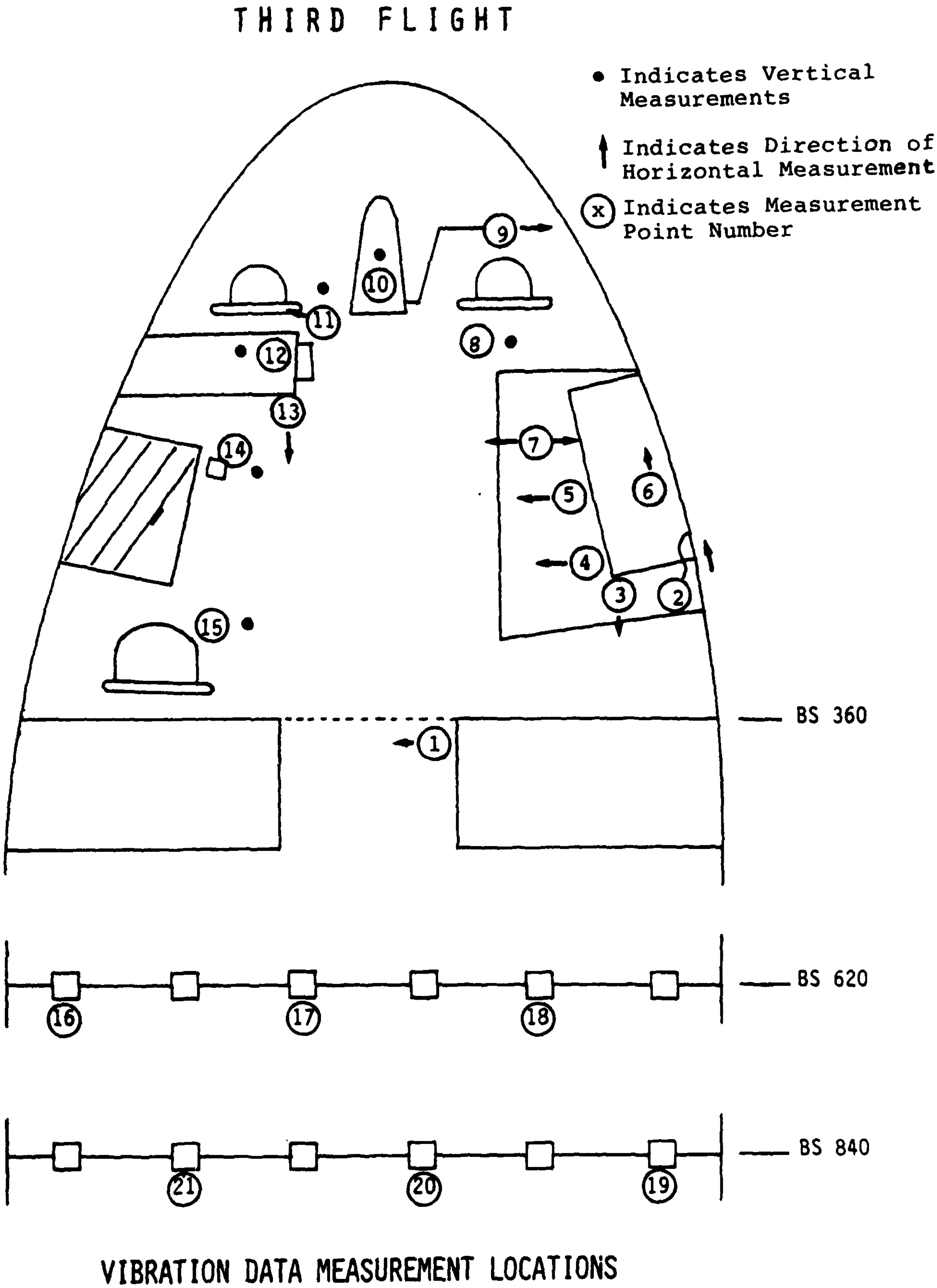


Figure 12. Measurement Locations for Third Flight.

TABLE 3

LOCATIONS AND FLIGHT CONDITIONS FOR MEASUREMENTS FOR THIRD FLIGHT

Pt	Flight Condition						
	No Rumble	Rumble 2	Rumble 3	Rumble 2 & 3	Rumble 1 & 4	Rumble 2 25,000 Ft	Rumble 2 25,000 Ft Hydraulics off
1	x	x	x	x	x	x	x
2	x			x	x		
3				x			
4				x			
5				x			
6				x			
7				x			
8				x			
9				x			
10				x			
11				x			
12	x	x		x	x		
13	x			x	x		
14	x			x	x		
15				x			
16	x	x	x	x	x	x	
17	x		x	x	x		
18				x			
19				x			
20	x			x	x		
21	x			x	x		

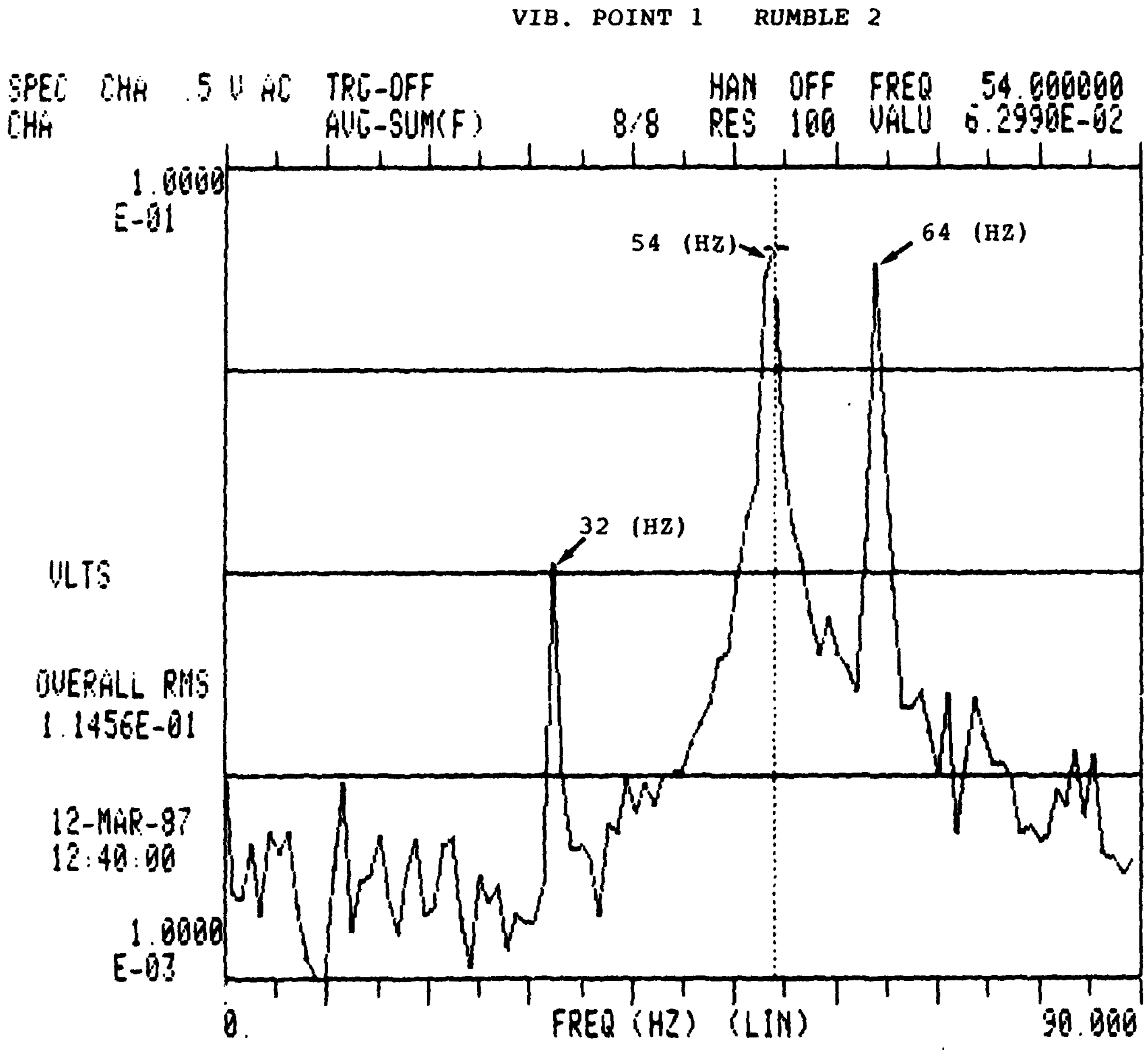


Figure 13. Typical Vibration Data Power Spectrum, Point 1.

Figure 14, it was the 50-Hertz to 60-Hertz response peak that was significantly higher in Rumble than out of Rumble. The measurements made in the cockpit area showed higher response levels than those made in the cargo area. It should be noted that the measurements made in the cargo area were made on or near the main wing support frames and we would expect this massive structure to be less responsive.

Comparing the vibration data and the acoustic data taken in the same area reveals some interesting facts. In all cases where comparisons were made, the highest two vibration response peaks and the highest two noise response peaks occurred in the 30-Hz to 40-Hz and 50-Hz to 60-Hz range. Figure 15 compares the noise and vibration data for several different locations. In the acoustic data, the difference in sound pressure level between the 30 Hz to 40 Hz and 50 to 60 Hz at positions numbers 1, 4, 12 and 11 are insignificant, meaning simply that they are practically equal in noise level. The vibration response levels at position numbers 3 and 8 are comparable for both frequency ranges. Although the two highest peaks in both acoustic and vibration data occur in the same two frequency ranges, an exact correlation of high vibration-high noise does not exist. These data conclude that the noise levels measured are far field in nature, meaning that the noise source was not acoustically near the noise measurement locations. This again indicated that acoustic absorbtion materials would need to be installed over the entire cockpit area to be effective and that there appears not to be a single noise source but multiple sources of nearly equal strength.

The complete set of data collected during the ground test is contained in Appendix C.

4.1.4 Ground Test

The force driving Rumble was obviously coming from the F-108 engines. It was not possible to collect engine

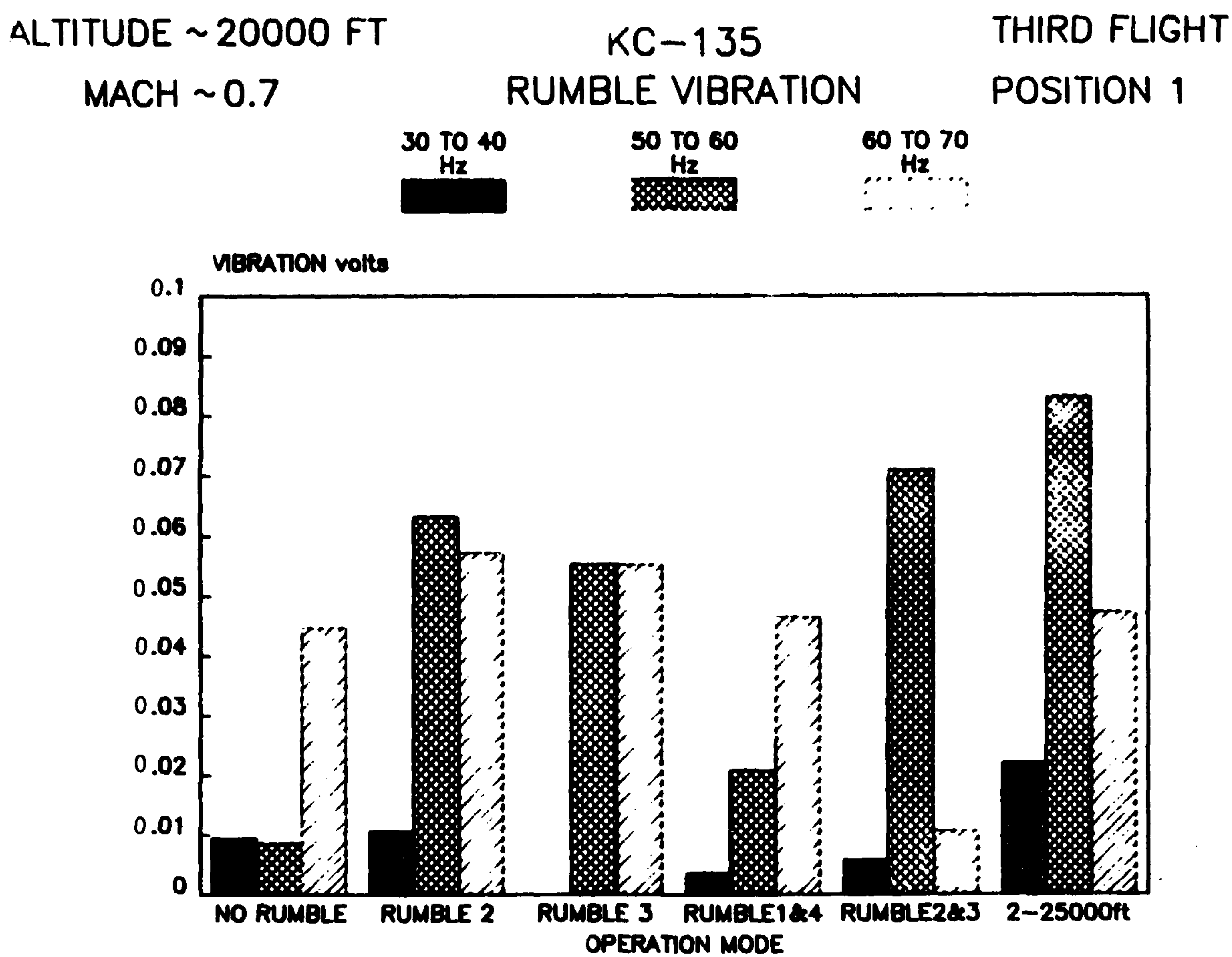
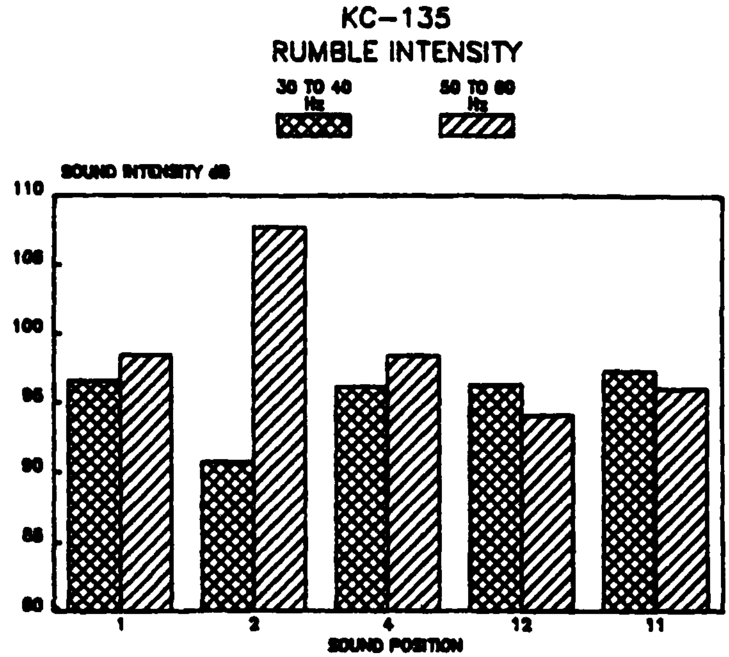
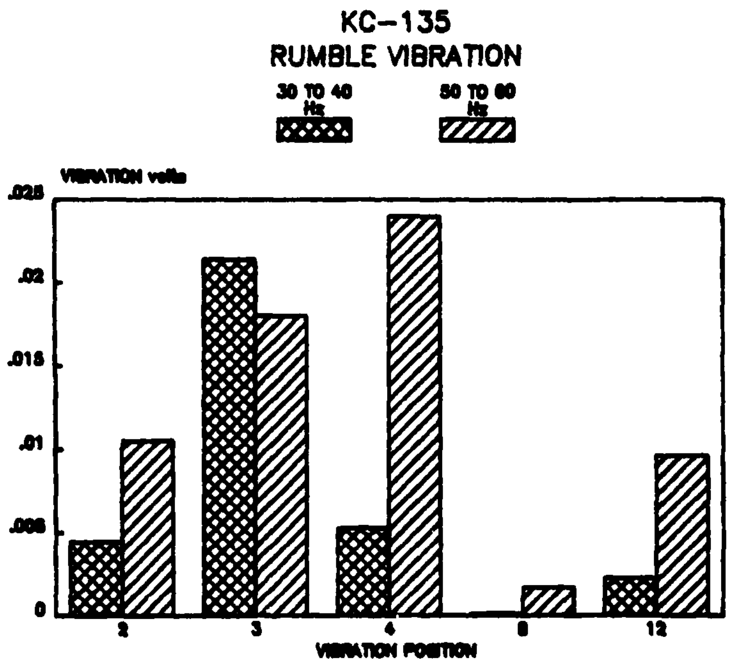


Figure 14. Typical Flight data for Third Flight.





RUMBLE 2&3 SECOND FLIGHT

Figure 15. Noise and Vibration Data From the Same Point for Several Different Locations.

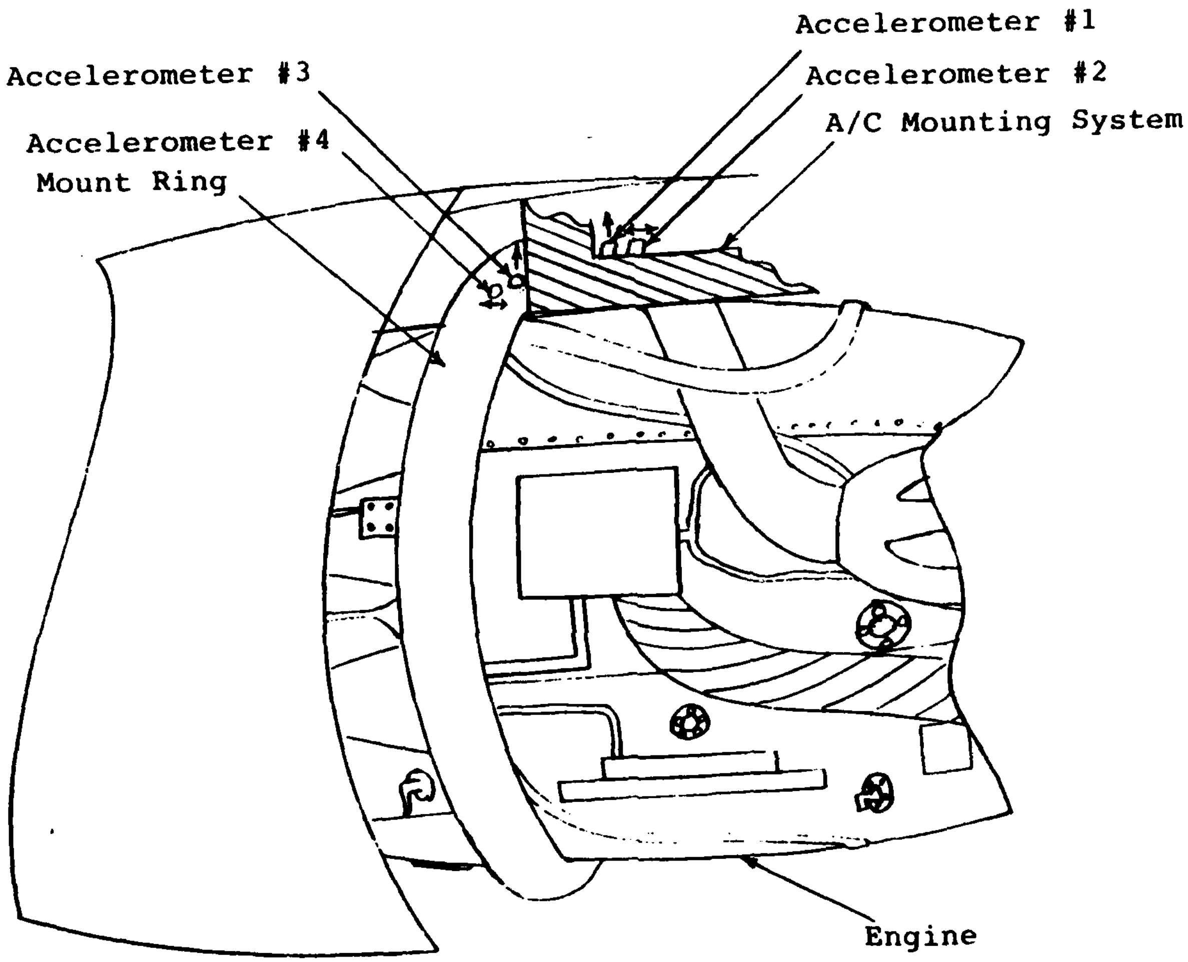
vibration data in flight during this test because of the problems associated with instrumenting the engines. Even though the in-flight conditions which produced Rumble would not be duplicated on the ground, it was decided that an engine ground test with accelerometers mounted on the engine would provide useful data. The objective of the engine run ground test was to determine the vibration response of the engine and aircraft nacelle area. Four accelerometers were mounted as shown in Figure 16 and a fifth accelerometer was located inside the aircraft at vibration measurement point 1. Table 4 lists the engine operating conditions under which measurements were made and the accelerometer locations and measurement directions. The four accelerometers and required signal conditioning were provided by OCALC Engineering Test Laboratory (MMET).

Figure 17 is a typical frequency response function taken from the aircraft nacelle during the ground test. The response peak at 55 Hz was seen at all engine speed conditions. Figure 18 is a typical response peak from the engine mount ring. Here again the 55-Hz peak was dominant. Note that the 55-Hz response plot matched the predominant Rumble frequency. The frequency response function for the engine mount ring exhibited significantly more response peaks than that of the aircraft nacelle. The increase in the number of response peaks was expected because of the plate and ring resonances associated with the mount ring structure. All the data analyzed during the ground test is contained in Appendix D.

4.2 MODAL ANALYSIS ON A/C 307

During the ground tests on A/C 307, the accelerometers mounted on the engine mount ring and aircraft mount bracket recorded high vibration levels in the 30-Hertz to 75-Hertz range which correspond in frequency to the peak acoustic and vibration data taken during flight tests. Therefore, it was decided to conduct a modal analysis of the engine, nacelle, and wing

GROUND TEST



ACCELEROMETER LOCATIONS

Figure 16. Measurement Locations for Ground Test.

TABLE 4

LOCATIONS AND CONDITIONS FOR MEASUREMENTS
ON GROUND TEST

Accel Location	Engine RPM (%)			
	69 - 70%	61.5%	85%	65.5%
1	x	x	x	x
2	x	x	x	x
3	x	x	x	x
4	x	x	x	x
5	x	x	x	x
1*	x	x	x	x
2*	x	x	x	x
3*	x	x	x	x
4*	x	x	x	x
5*	x	x	x	x

*Same location frequency range 1,000 Hz instead of 100 Hz

ACCELEROMETER NUMBER	MEASUREMENT DIRECTION	LOCATION
1	Vertical	A/C Spar
2	Fore and Aft	A/C Spar
3	Vertical	Engine Mount ring
4	Fore and Aft	Engine Mount ring
5	Side to Side	A/C Frame in Cabin (Vib position 1)

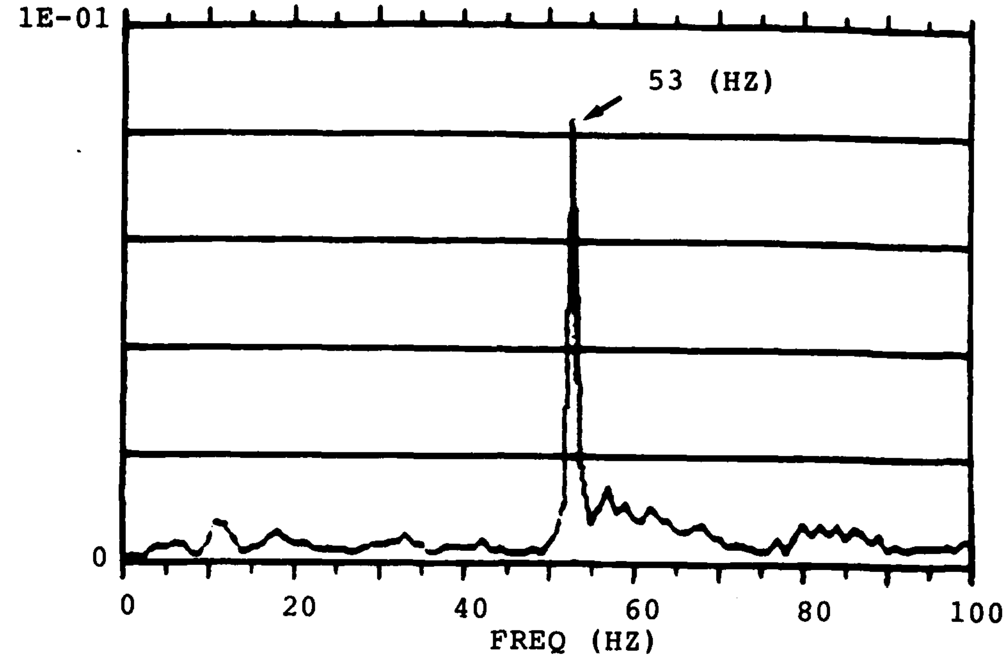


Figure 17. Typical Frequency Response
Aircraft Nacelle Area.

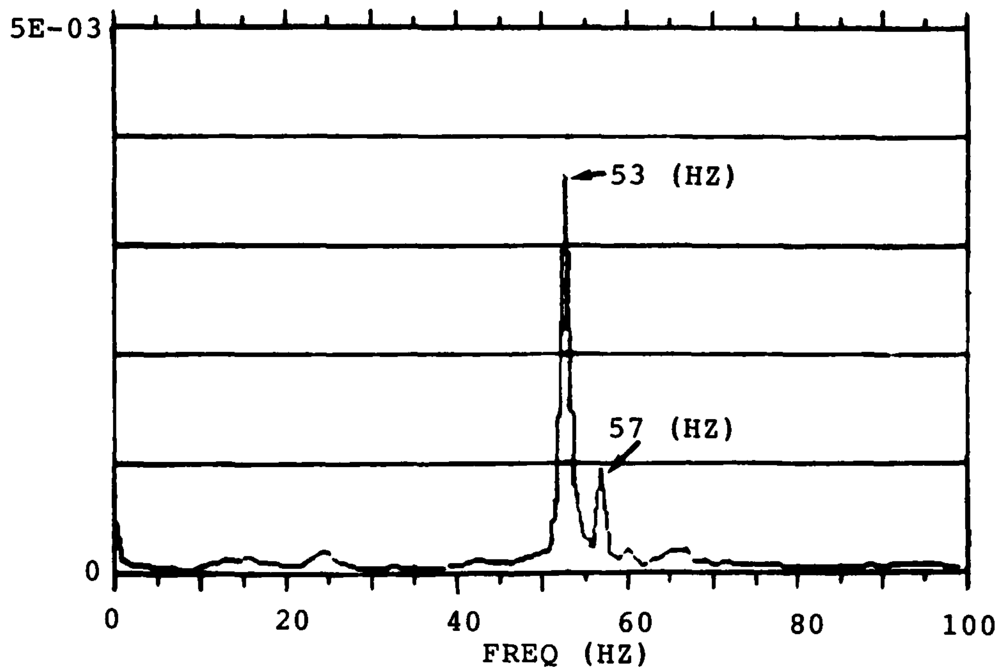


Figure 18. Typical Frequency Response
Engine Mount Ring.

structural system to determine the nature modes of vibration of this structural system and define to what degree resonance of the structure was contributing to the Rumble problem.

A Zonic Model Xcite 1001P-110 Hydraulic Shaker was used to excite the engine/aircraft system and the input and response data were collected on a Gen Rad 2510 Micromodal analyzer. The driving point was on the engine accessory case as shown in Figure 19.

Triaxial frequency responses functions were taken at the following 29 locations:

(1) Eleven points on the engine center line along the right side of the engine (Figure 19),

(2) Eleven points on the nacelle (Figures 20 and 21),

(3) Three points along the top of the engine and nacelle cowling (Figure 22), and

(4) Four points on the underside of the wing as shown in Figure 23.

The frequency response data were collected over the frequency range of 0 to 100 Hertz. The excitation force input at the driving point was measured using a PCB force gage and the acceleration response data were measured using three 2221D accelerometers. A typical frequency response function is shown in Figure 24.

The modal analysis identified several vibration modes in the frequency range of 0 Hertz to 100 Hertz. The four modes identified were 18 Hertz, 32.81 Hertz, 32.95 Hertz and 50 Hertz.

In Figure 25, the first mode (18 Hertz) had the engine moving from side to side in a twisting motion around the back mount bracket.

In Figure 26, the second mode (32.81 Hertz) showed the engine again twisting from side to side as well as rocking up and

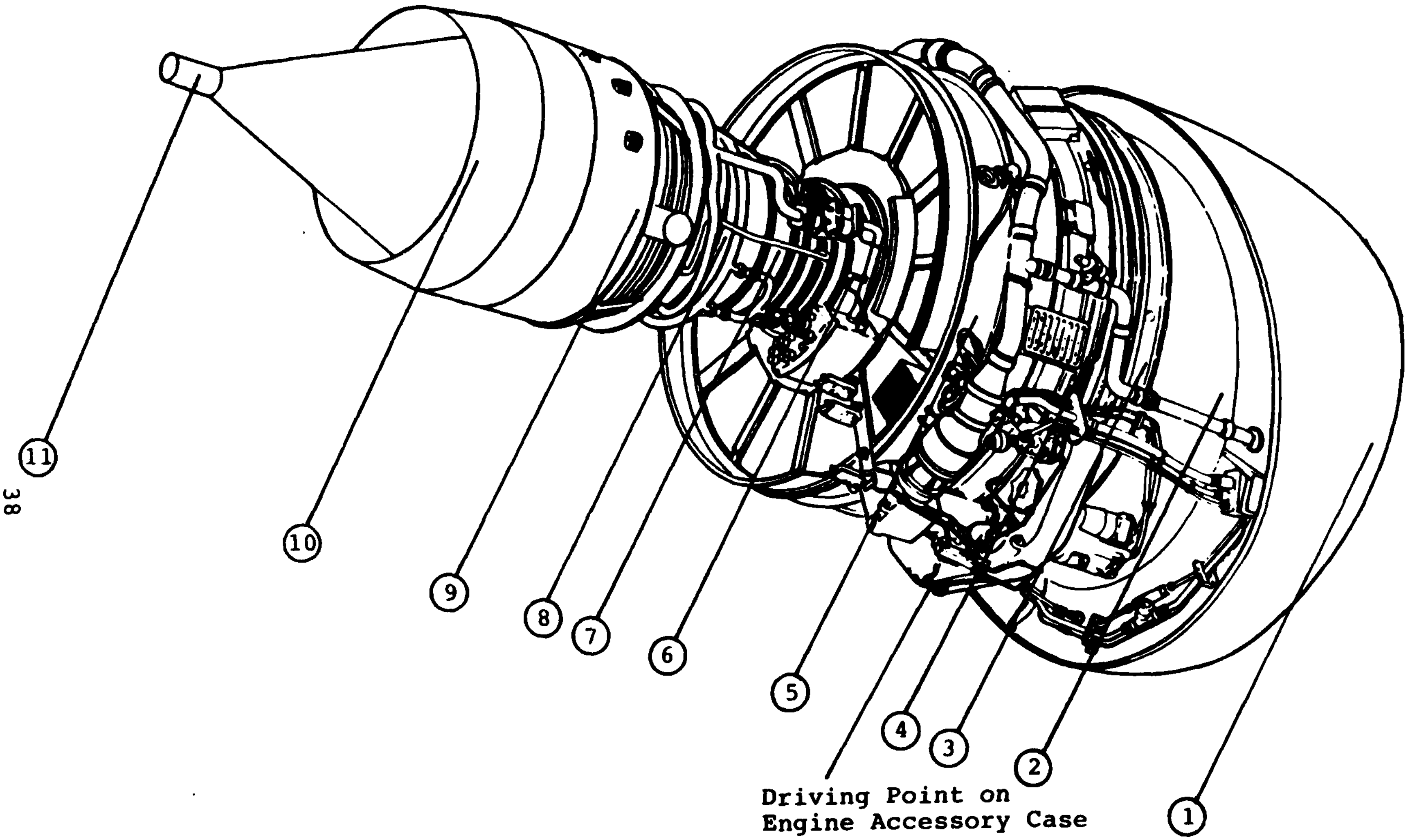
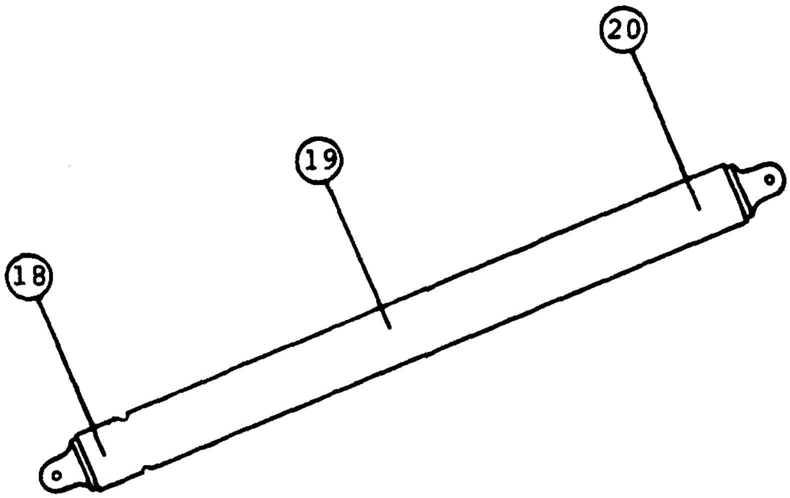


Figure 19. Data Points on Engine



Data Points on Strut
Diagonal Bracket

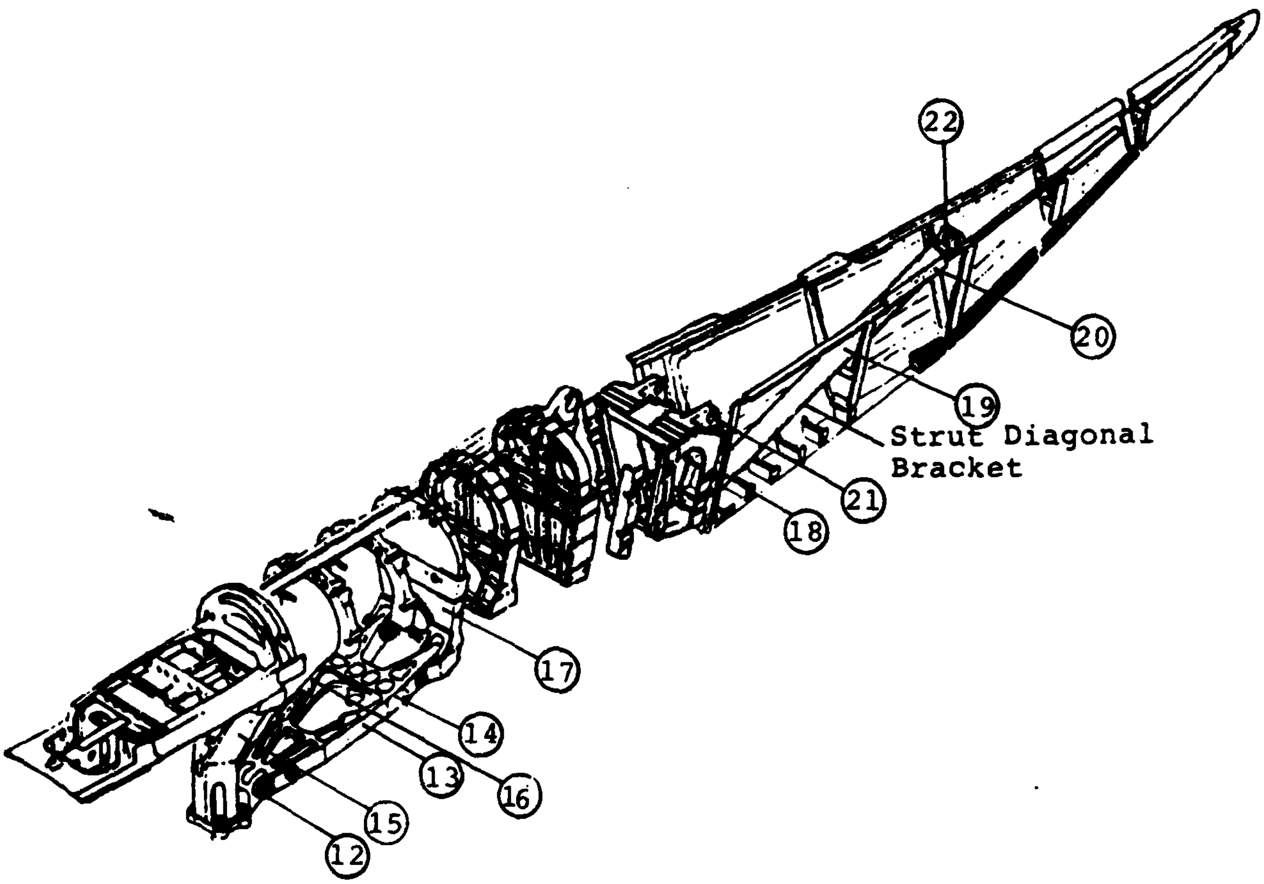


Figure 20. Location of Strut Diagonal Bracket.

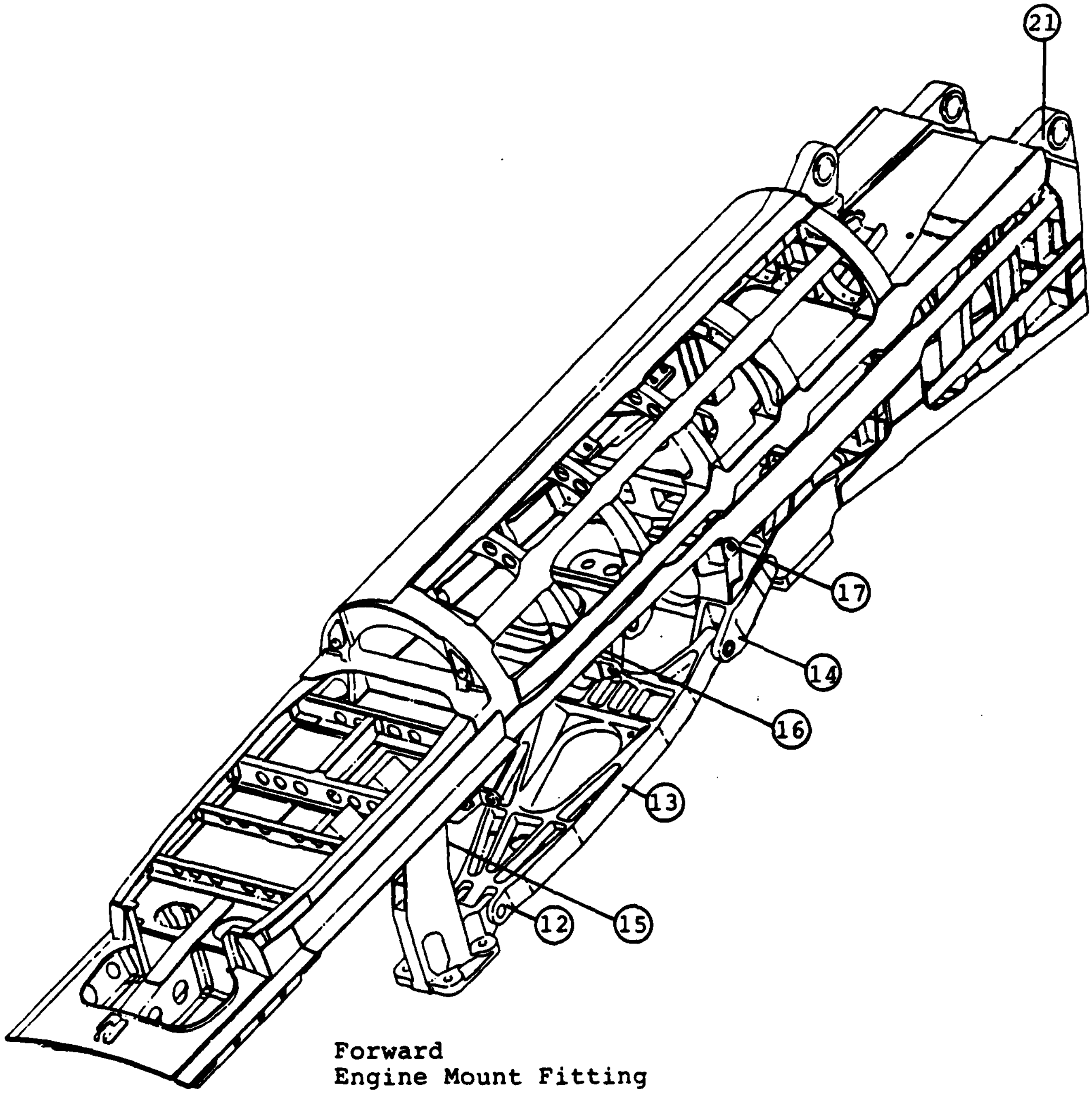


Figure 21. Data Points on Forward Engine Mount and Thrust Bracket.

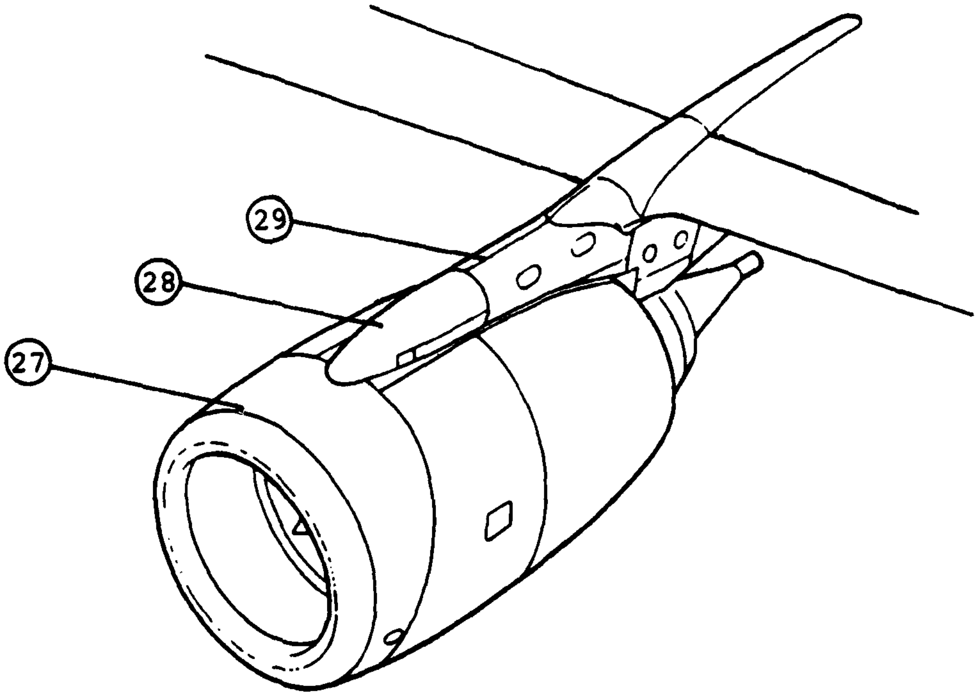


Figure 22. Data Points on Top of Engine and Nacelle Cowling.

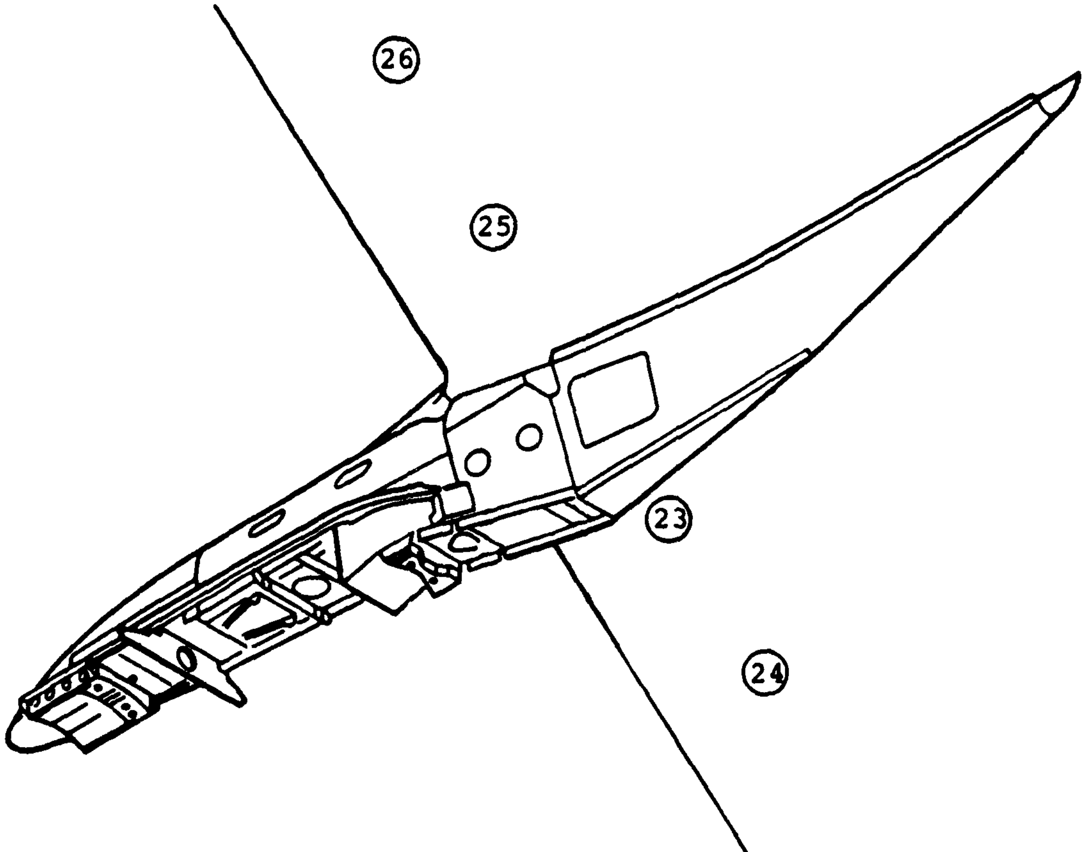


Figure 23. Data Points on Underside of Wing.

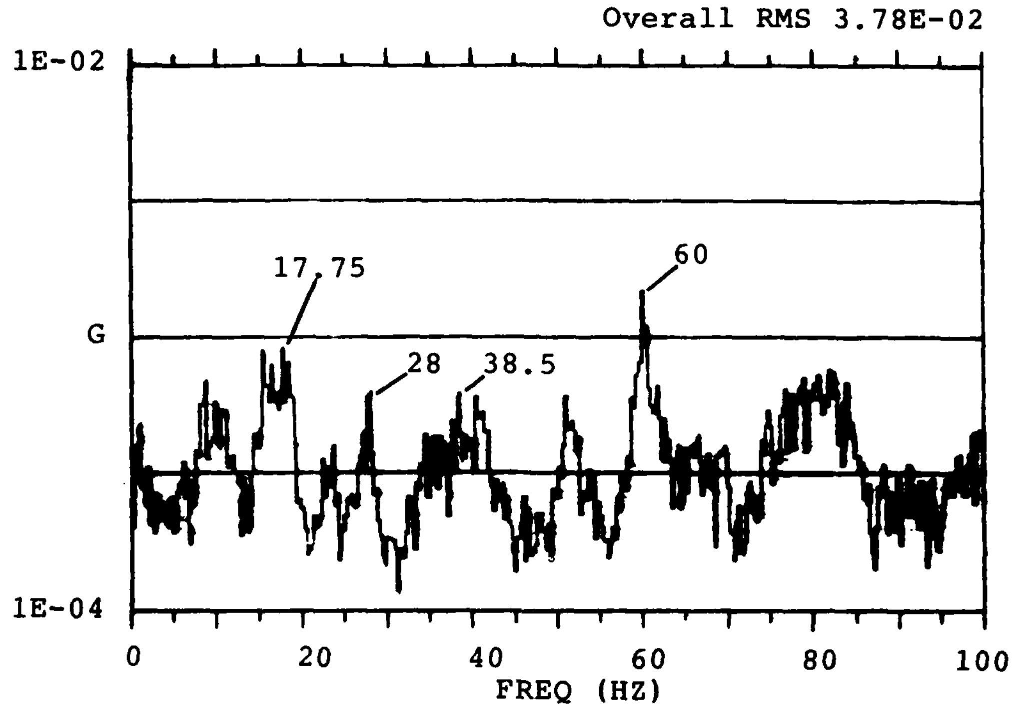
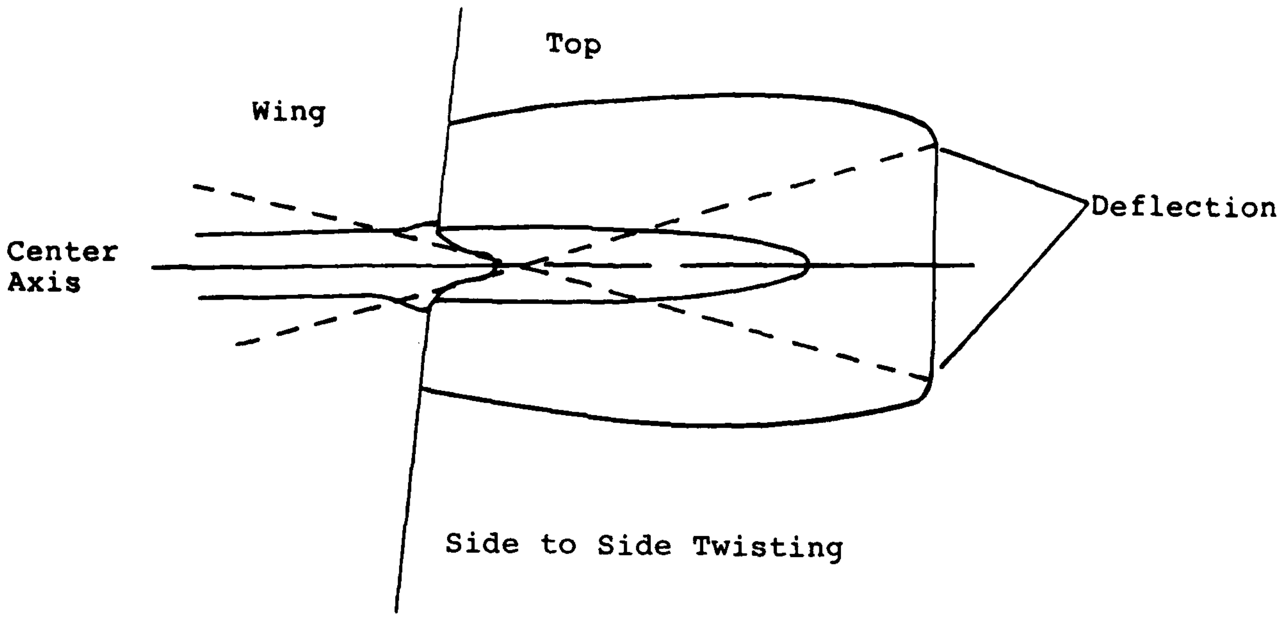


Figure 24. Typical Modal Frequency Plot.



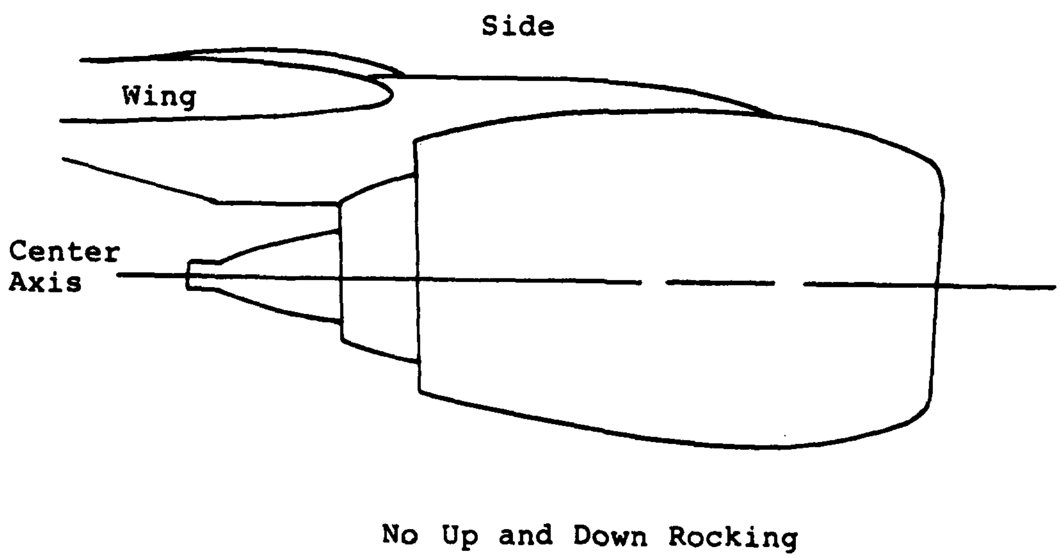


Figure 25. 18 Hz Mode Shape.

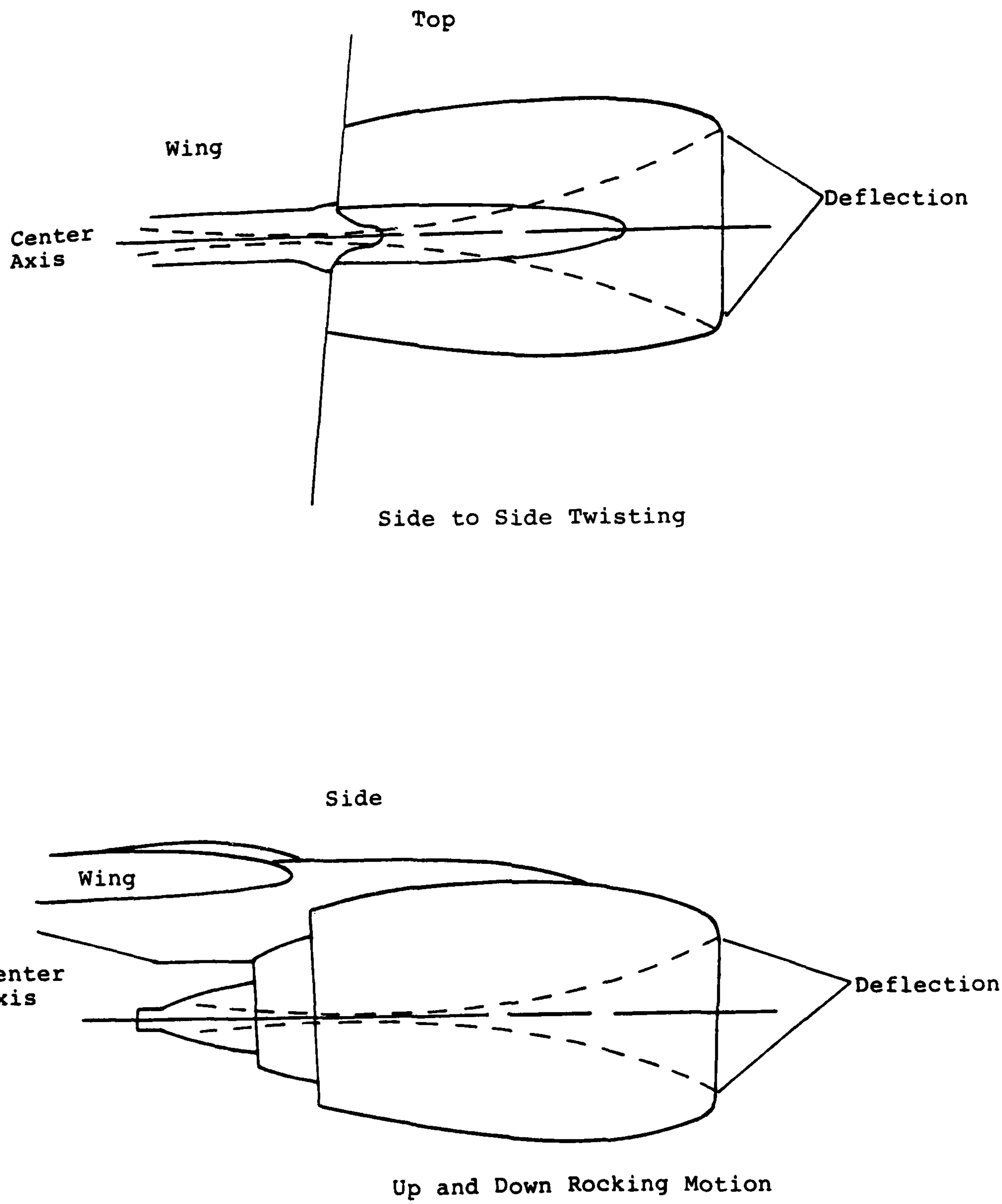


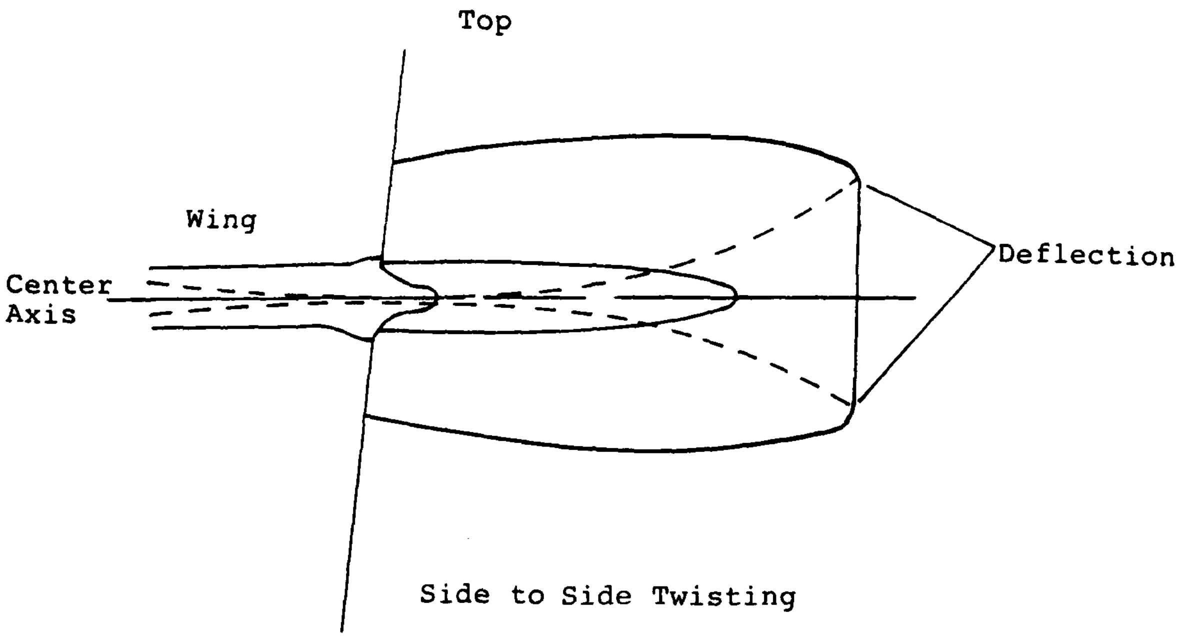
Figure 26. 32.81 Hz Mode Shape.

down, resulting in the front of the engine moving in an elliptical orbit.

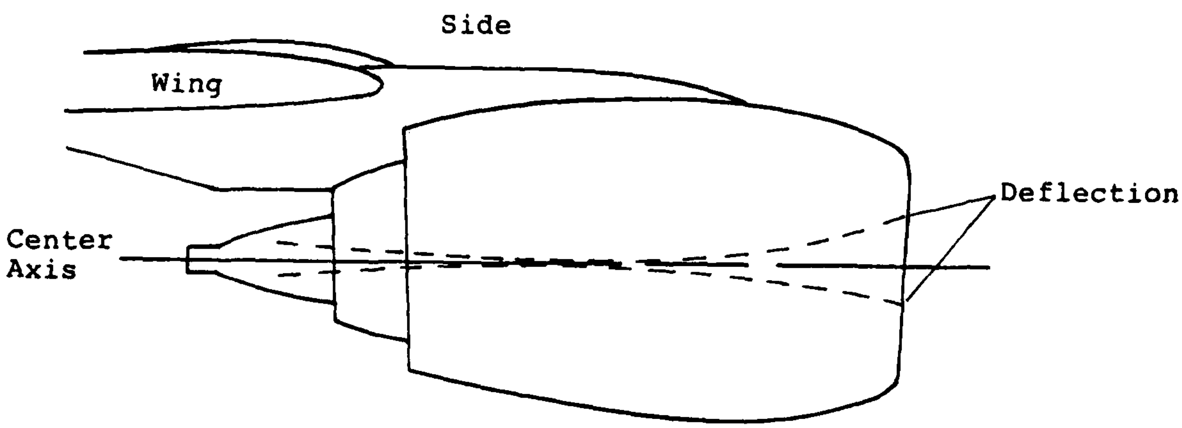
In Figure 27, the third mode (32.95 Hertz) revealed the twisting from side to side, as does the previous mode, but with reduced rocking motion.

In Figure 28, the fourth mode (50 Hertz) showed the engine with a side to side twisting motion. The twisting and rocking motion of the engine appeared to pivot from the back engine mount.

We should note that the modal analysis was completed on a static aircraft. The aircraft was sitting on its landing gear in the hanger. The engine/airframe structure was loaded only by gravity. In flight, the normal preloads on the structure would include the engine thrust and the aerodynamic wing loads. Typically, we would expect that the in-flight structural loads would cause the in-flight resonant frequencies to be higher than those measured during this ground test. Also, the driving force was applied at a single point in a vertical direction which would excite primarily vertical motion. A result of this method of excitation was that modes with little or no vertical motion were difficult to excite and modes which had a nodal point (no motion) at the drive point were not excited. For these reasons, UDRI believes that there are numerous other system resonant modes in the 18- to 80-Hertz range.

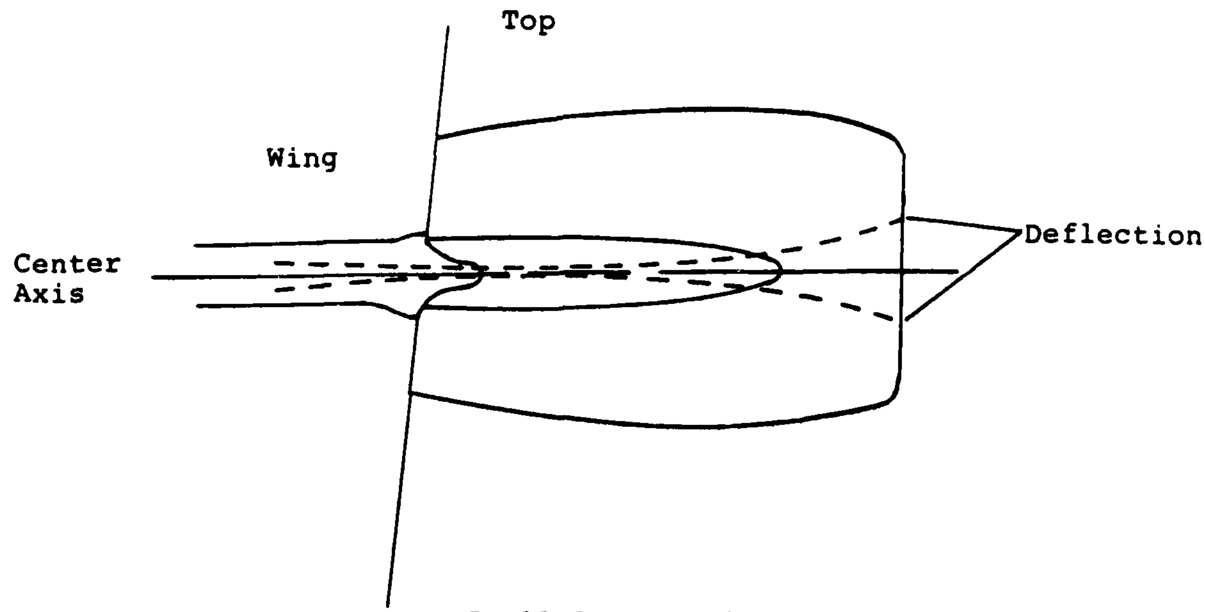


Side to Side Twisting

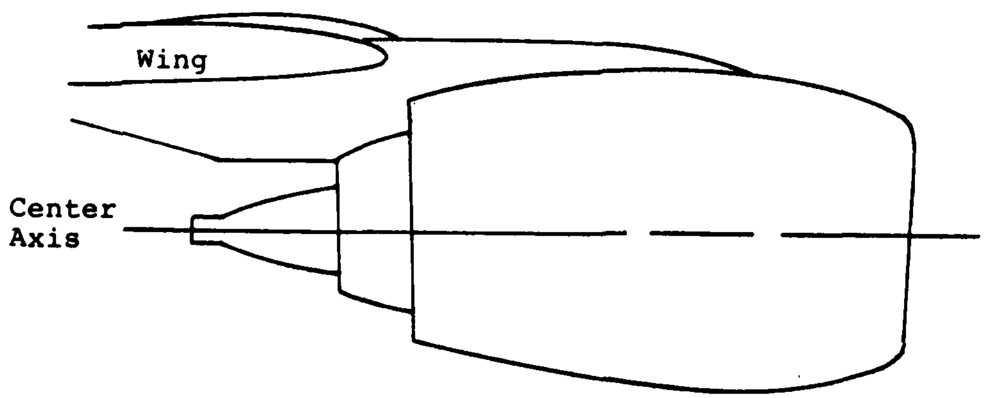


Small Amount of Up and Down Rocking

Figure 27. 32.95 Hz Mode Shape.



Small Amount of Side to Side Twisting



No Up and Down Rocking.

Figure 28. 50 Hz Mode Shape.

5.0 McCONNELL TEST PROGRAM

The test program at McConnell AFB consisted of two separate efforts which were:

(1) a flight test effort, and

(2) a ground test on the inboard engines.

There were two complete sets of dynamic instrumentation and data recording systems used during the tests at McConnell. All the instrumentation and one recorder were provided by OCALC/MMET. The second recorder and backup instrumentation were provided by UDRI. The specific data to be recorded were defined by UDRI while the test coordination with the flight crews was the responsibility of Major D. Huston from OCALC/MMSRE. Michael Drake supervised both the ground tests. The flight test data were collected by a two person instrumentation crew while the ground test data were collected by a three-person instrumentation crew. In all but the last flight test, the instrumentation crew was composed of both UDRI and OCALC personnel. The OCALC personnel involved in the McConnell test effort were Major D. Huston (MMSRE), and Larry Gore and Joe Winfree (MMET). The UDRI personnel involved in the McConnell test were Michael Drake and Dennis Davis. The following paragraphs describe the tests conducted and the analysis of the data collected.

5.1 FLIGHT TEST

The objective of the flight test effort was to obtain Rumble data from several aircraft under multiple flight conditions to make conclusions from a broad data base on Rumble events. Before this effort, only two aircraft had had instrumented Rumble data collected. The data from these two flights (A/C 307 and the Boeing test) seemed significantly different and apparently unrelated.

The objective of the flight test was accomplished by testing six aircraft. The aircraft tested and other relevant data about

the individual flights are listed in Table 5. The instrumentation used for all flights consisted of three accelerometers located as shown in Figure 29. These locations were chosen as a result of the analysis on the flight test data collected on A/C 307. The accelerometer output for all three accelerometers was recorded at various times throughout the flight for Rumble and no Rumble conditions and analyzed later on the UDRI Gen Rad 2510 Analyzer.

Table 5 shows that all the aircraft except A/C 306 exhibited a very low level of Rumble. The analysis of the data on A/C's 120, 308, 312, 482 and 502 was conducted at the maximum Rumble in the flight. Analysis of the data on A/C 306 was conducted on six different Rumble events during the flight. The complete set of data analyzed from all the flights is given in Appendix E.

Table 6 summarizes the analysis of Flights 120, 308, 312, 482 and 502. Reviewing the data in Table 6 revealed that in two of the five flights, the peak response at the Navigator's Station was slightly higher out of Rumble than in Rumble (120 and 482). However, the other three flights showed that the peak response in Rumble can be as much as four times higher than the levels seen out of Rumble. Comparing the overall RMS (from 0 to 100 Hertz) between Rumble and no Rumble for all flights indicated that the Rumble overall RMS was approximately double the no Rumble. We should note that the maximum peak response reported is 0.04 g's which was a small acceleration and occurred on a secondary structure which supports some of the Navigator's instrumentations.

The analysis of the data presented on the Wing Spar vibrations revealed that in all cases the Rumble vibration was higher than the vibration levels seen in normal flight. The increase ranged up to a factor of 3. The Rumble, no Rumble overall RMS comparisons do not show a consistent trend.

TABLE 5

FLIGHT TEST AIRCRAFT DATA

A/C No.	Flight Date	Flight Duration Hours	Level of Rumble	Serial No. of Engine on A/C Pos.1	Pos.2	Pos.3	Pos.4	Time on Engines (Hrs) Positionâåc câ 1	2	3	4
120	8/25/87	3.5	Low	CF711 191	CF717 212	CF711 225	CF711 226	529	529	529	529
482	8/25/87	2.25	Low	CF711 189	CF711 177	CF711 178	CF710 180	746	746	746	746
312	8/25/87	4.5	Low	CF711 121	CF710 216	CF710 150	CF710 136	419	348	782	782
502	8/26/87	3.75	Low	CF710 195	CF710 157	CF710 206	CF711 215	296	377	296	296
308	8/26/87	3.5	Low	CF710 159	CF711 135	CF711 157	CF710 160	293	293	293	293
306	8/26/87	3.0	High	CF710 156	CF710 163	CF710 148	CF710 158	848	848	848	848

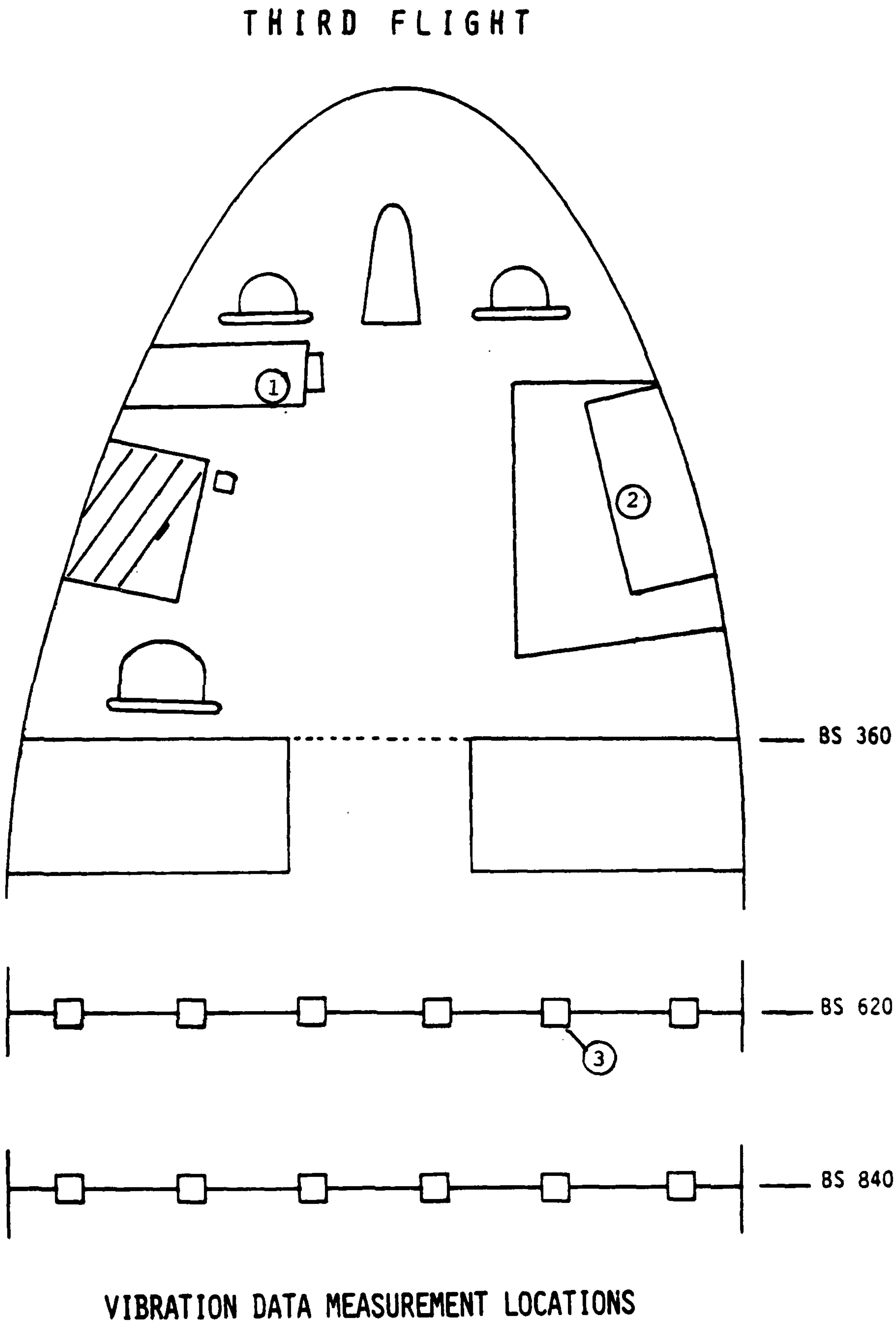


Figure 29. Measurement Locations for McConnell Flight Tests.

TABLE 6
FLIGHT DATA FOR A/C 120, 308, 312, 482, AND 502

	NO RUMBLE						RUMBLE					
	Nav Station			Wing Spar			Nav Station			Wing Spar		
A/C	Freq	Amp	Overall	Freq	Amp	Overall	Freq	Amp	Overall	Freq	Amp	Overall
120	61.0	.0056	.0139	61	.008	.0200	54	.00428	.0162	65.0	.008	.0102
308	73.5	.0038	.00961	73	.009	.0181	67	.0136	.0197	67.0	.025	.0249
312	63.0	.01	.0218	66	.006	N/A	56	.0407	.0479	54.5	.0085	.0193
482	32.0	.009	.0126	64	.012	.0232	66	.00634	.0213	--	--	--
502	65.0	.0042	.0134	--	.003	.0194	73	.0106	.0171	73.0	.0085	.0149

NOTE: Amp. and Overall in g's; Freq. in Hertz.

The above discussion focused on the maximum amplitudes seen in the frequency range of 20 to 80 Hertz. Figures 30 through 33 show the precise frequency response functions for the data in Table 6 for A/C 502. Comparing Figure 29 (Navigator's Station - no Rumble) and Figure 32 (Navigator's Station - Rumble) illustrates the typical changes in peak response amplitude and the frequency content seen. It is the change in frequency content that produced the peak/fade interference pattern of two closely spaced peaks (in the frequency domain) which produced the "Whaa, Whaa" sound which the flight crew identified as Rumble.

Another point on frequency can also be made from Table 6; the maximum response peak seen during Rumble varied from 54 to 73 Hertz. This variation indicated that there must be multiple resonant modes causing Rumble because such a change in frequency for a single mode would indicate at least a 50 percent change in structural stiffness (i.e., variation from plane to plane in structural stiffness) which is totally unrealistic.

From the data in Table 6 we can conclude that no significant change in structural integrity will result due to Rumble.

Six different Rumble conditions were analyzed from the flight of A/C 306. This A/C exhibited the highest levels of Rumble seen during the entire program. Table 7 summarizes the data analyzed from the flight on A/C 306.

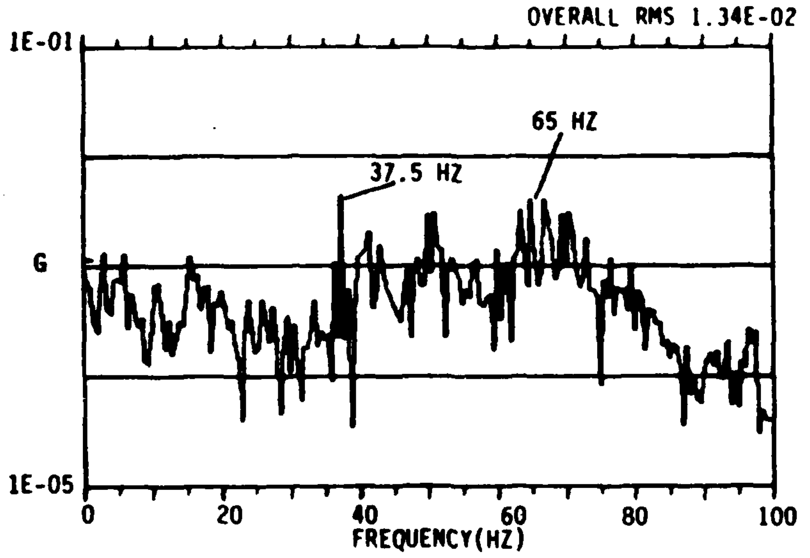


Figure 30. Navigator's Station No Rumble

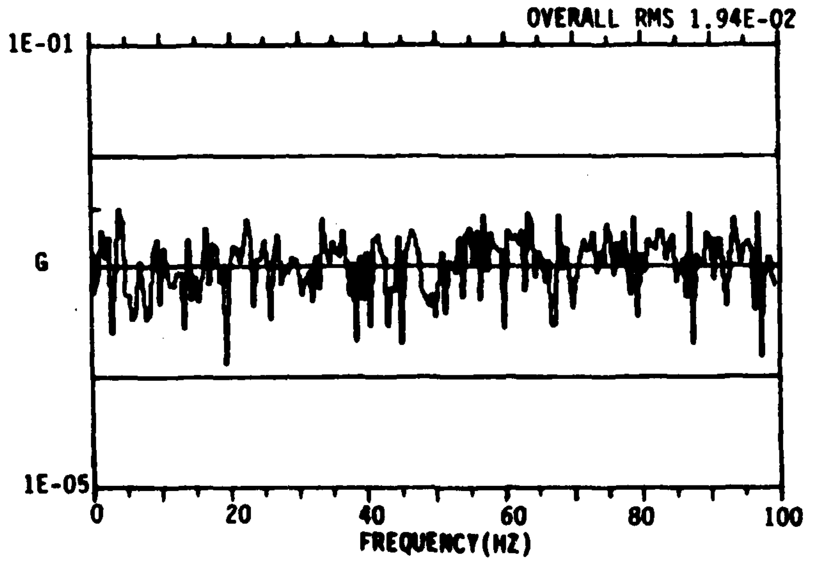


Figure 31. Main Spar Leading Edge No Rumble

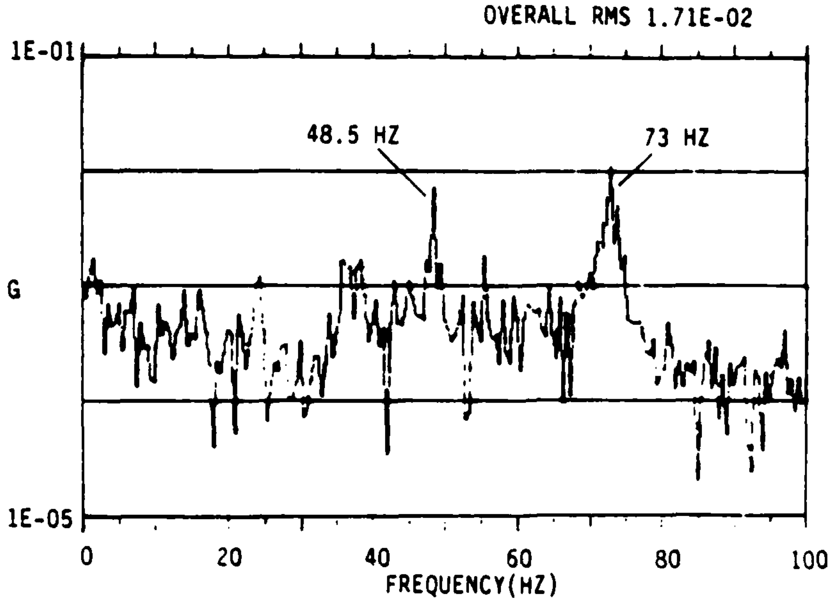
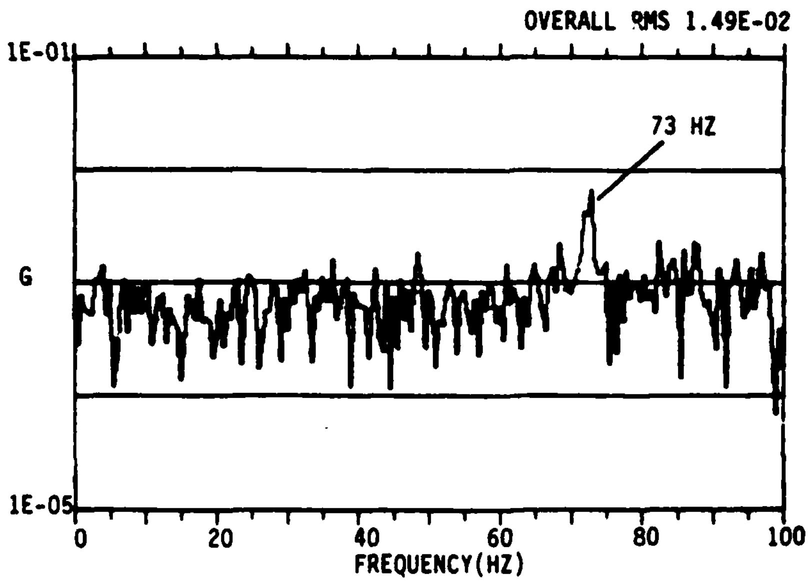


Figure 32. Navigator's Station Rumble



Main Spar Leading Edge

Figure 33. Wing Spar Rumble

TABLE 7
FLIGHT DATA FROM A/C 306

Flt. Seg-ment	NO RUMBLE Nav Station Freq	Amp	Overall	Wing Spar Freq	Amp	Overall	RUMBLE Nav Station Freq	Amp	Overall	Wing Spar Freq	Amp	Overall
A	62	.007	.0183	63.5	.003	.017	69.5	.0181	.0314	68.5	.015	.0215
B	62	.007	.0183	63.5	.003	.017	59.5	.0138	.0218	59.5	.011	.0213
C	62	.007	.0183	63.5	.003	.017	51.5	.0107	.0235	48.0	.008	.0170
D	62	.007	.0183	63.5	.003	.017	55.5	.033	.055	55.5	.009	.0190
E	62	.007	.0183	63.5	.003	.017	66.5	.009	.0213	--	--	-190
F	62	.007	.0183	63.5	.003	.017	55	.0638	.0686	55.0	.0085	.0153

NOTE: Amp. and Overall in g's; Freq. in Hertz.

From Table 7, the Navigator's Station and Wing Spar both show an increase in peak vibration response from the no Rumble to Rumble flight condition. The Navigator's Station increase varied by a factor of 1.29 to 9.11. The Wing Spar peak response increased by a factor of 2.67 to 5.0. The overall RMS for the Navigator's Station varied by a maximum factor of 3.75 while the Wing Spar maximum increased a factor of 1.26.

Comparing the absolute levels seen in Rumble and the increases between no Rumble and Rumble for A/C 306 to the data in Table 6 indicated that the Rumble in A/C 306 was slightly higher in level than that seen in the other A/C. However, the conclusion that no structural problems should result from Rumble still holds because the levels, although higher, are insufficient to cause problems.

Conclusions from the frequency data in Table 7 also support the conclusions drawn from Table 6. Figure 34 presents the frequency response function from the Navigator's Station for Rumble Event D. Comparing Figure 34 to Figure 35 which presents similar data for Rumble Event E illustrated that the modal

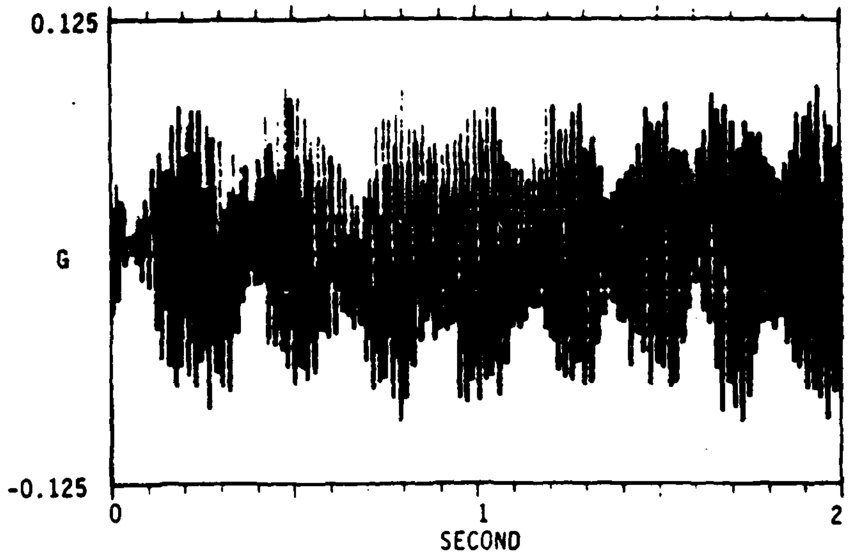


Figure 34a

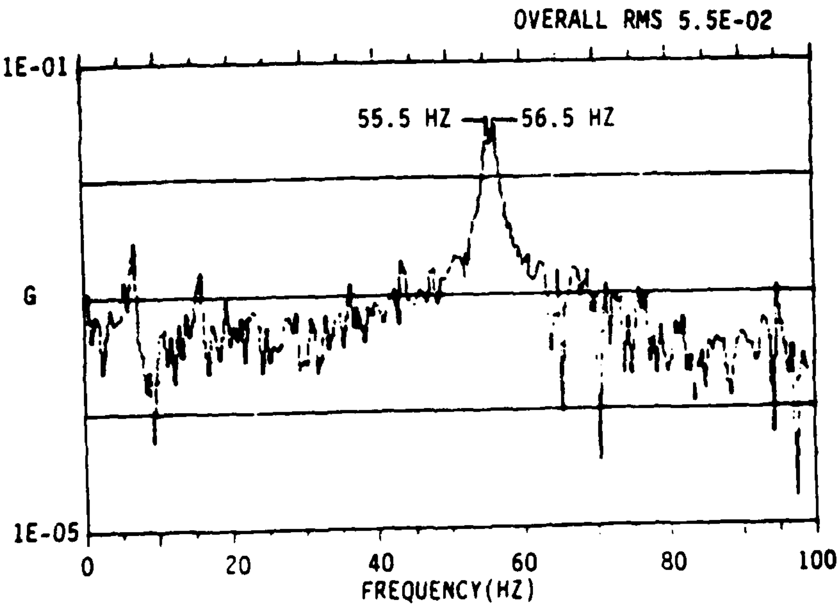


Figure 34b

Figure 34. Frequency and Time Response for Rumble D, Navigator's Station.

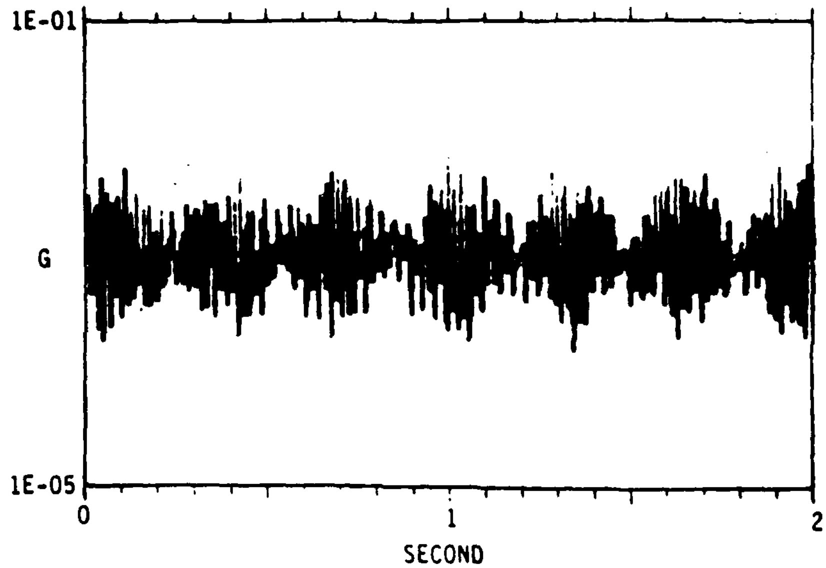


Figure 35a

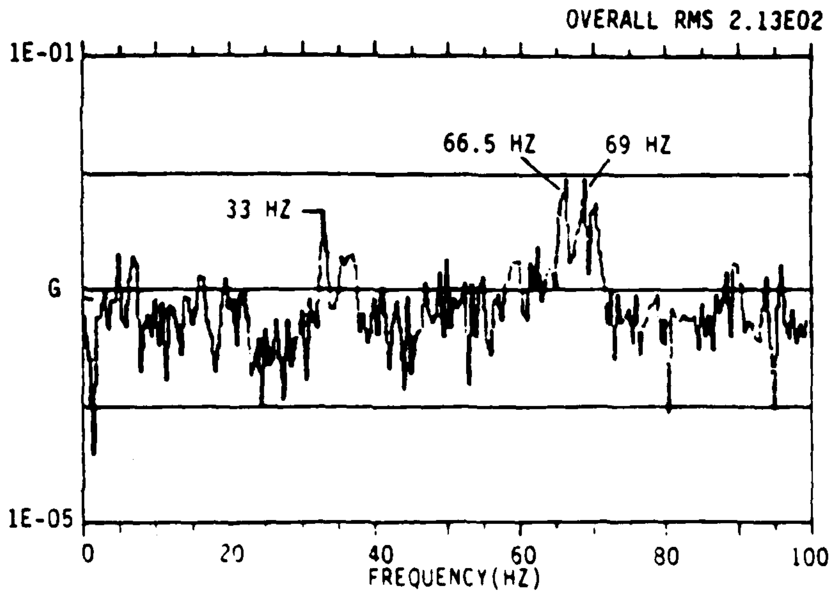


Figure 35b

Figure 35. Frequency and Time Response for Rumble E, Navigator's Station.

participation for each event was significantly different. Notice; however, that the time domain data for both events (Figures 34a and 35a) contained the basic peak and fade or "Whaa, Whaa" characteristics of Rumble. These factors further support the theory that it was not a sound level increase or a specific frequency which was identified as Rumble but the "Whaa, Whaa" characteristic that the crew called Rumble regardless of the actual frequency.

5.2 GROUND TEST

The objective of the ground test efforts at McConnell AFB was to further substantiate the link between engine/nacelle vibrations to the Rumble felt in the aircraft. A total of four engines were instrumented and tested (Table 8). Note that only the inboard engines were instrumented because the inboard engines were the principal drivers of Rumble.

There were three accelerometers mounted for each ground test. The accelerometers were located at:

- The Navigator's Station as was done in flight
- The engine case on the engines in Positions 2 and 3 at the connector for the number 1 bearing vibration transducer which is used to monitor engine vibration during test cell and "on the wing" balance checks.

TABLE 8

GROUND TEST AIRCRAFT AND ENGINES

A/C Number	Engine Serial Number Position 2	Position 3
120	CF 711 212	CF 711 225
306	CF 710 163	CF 710 148

The accelerometer responses were recorded on tape and analyzed later by UDRI.

After the engines had been started and allowed to warm up properly, the engine was cycled through several slow accelerations to maximum ground power level, several slow decelerations from maximum power level, several rapid decelerations from maximum power and a 2-minute hold at maximum power. After the completion of these engine excursions, the engine was taken through the proper cool-down and shut-down procedures. Data were collected and analyzed for the entire engine ground operation.

Table 9 presents the significant results of the analysis of the ground run data for both A/C 120 and A/C 306. Although the Navigator's Station (Nav Peak in Table 9) acceleration response did not duplicate the in-flight Rumble response, the frequencies of high response on the engines fall in the same frequency band for Rumble on both aircraft.

The frequency response functions for the ground test data are given in Appendix F.

TABLE 9

GROUND TEST RESULTS

A/C #	Eng #	Frequency	% N1	Engine Peak Amplitude	Nav Peak Amplitude
120	2	61.0 Hz	41%	0.0065	0.00511
120	3	60.5 Hz	41%	0.00225	--
120	2	63 Hz	73%	0.00795	0.0108
120	3	63 Hz	73%	0.00211	--
120	2	50.5 Hz	Descent	0.00279	0.013
120	3	--	--	--	

A/C #	Eng #	Frequency	% N1	Engine Peak Amplitude	Nav Peak Amplitude
306	2	--	--	--	
306	3	53.5 Hz	52%	0.00509	0.0122
306	2	66.0 Hz	80%	0.00239	--
306	3	65.0 Hz	80%	0.00592	0.00816
306	2	72.5 Hz	84%	0.00242	--
306	3	71.5 Hz	84%	0.00348	0.0176
306	2	62.0 Hz	Descent	0.00316	--
306	3	61.5 Hz	Descent	0.00833	0.00298

6.0 ENGINE VIBRATION

All data from the Rumble events studied pointed to the F-108 engine as providing the excitation force which generated Rumble. To further understand Rumble and its causes, three reviews relating to engine vibrations were undertaken, the specific objectives and results to which are discussed in the paragraphs below.

6.1 VIBRATION COMPARISONS OF THE F-108 AND J-57 ENGINES

Rumble occurred in "R" models but was not reported in "A" models; therefore, a comparison of the F-108 (the "R" model engine) and the J-57 (the "A" model engine) was appropriate. This evaluation considered three areas which were:

- Comparison of the acceptance run vibration specifications.
- Comparison of the vibration force level input into the wing support structure.
- Comparison of the operational frequency range of each engine.

The standard engine acceptance run vibration instrumentation system consists of two to three vibration transducers mounted at various locations on the engine. Typically, the vibration data are filtered by two narrow band tracking filters; one tracking N1 (low speed spool RPM) and the other tracking N2 (high speed spool RPM). This data collection system allows the evaluation of the imbalance force generated by both engine shafts. Individual vibration limits are set for the N1 vibrations, the N2 vibrations and the overall (i.e., the unfilter) vibrations. Both the F-108 and the J-57 use this type of acceptance run vibration specification and collection system. Also, both engines are specified at an overall limit of 0.004 inch vibration displacement.

Since both engine vibration specifications set the same overall displacement limit, it would appear that the vibration input into the wing structure would be equal. Further consideration of the physical vibration which was occurring reveals that the vibration input from these two engines was indeed not equal.

The F-108 without the accessory package weighs approximately 4610 pounds. The J-57 without the accessory package weighs approximately 3400 pounds. Therefore, the F-108 weighs 1210 pounds more than the J-57 or the "R" model engine represents an increase in engine weight of 36 percent over the "A" model. (Note that this does not include the weight of the accessory package. The "R" model accessory package does weigh more than the "A" model system; however, exact weights were not obtained.)

Using the facts that both engines were limited to the same displacement and that the F-108 is at least 36 percent heavier than the J-57 in combination with a simple single degree of freedom system leads us to an important conclusion. In a simple vibration system, vibrating in the steady state, the system energy is constant and is stored in a combination of kinetic and potential energy. At one point in the vibration cycle, the system energy consists totally of kinetic energy. The kinetic energy (KE) is equal to one half the mass (m) times the velocity squared (V^2), ($KE = 1/2mV^2$). Since the displacement is fixed (0.004 inch for both engines), the velocity is given by V_{F-108} = (0.004) $_{F-108}\cos$ $_{F-108}t$ and V_{J-57} = (0.004) $_{J-57}$ cos $_{J-57}t$ if the frequencies ('s) are approximately equal then

$$KE_{F108} = 1/2m_{F108}V^2$$

which is greater than

$$1/2m_{J57}V$$

because

$$m_{F108} = 1.36 m_{J57}$$

In reality, the engines are not simple systems so the exact increase in vibration input to the wing cannot be defined from this simple model; however, we can state that the F-108, even though it has the same vibration specifications, does input more force into the wing than the J-57.

The operational speed of the F-108 covers a one per revolution frequency range of 20 to 80 Hertz. The operational speed of the J-57 covers a frequency range of 64 to 114 Hertz.

The combination of the engine vibration specifications, the engine weights, and the engine operational speeds (frequencies) leads to the following:

- The Rumble could not be seen on the "A" model because the J-57 forcing function is too high in frequency.
- Since the F-108 and J-57 have the same vibration specifications, and the F-108 is heavier than the J-57, the F-108 will input more vibrational force into the wing than the J-57.

6.2 F-10? VIBRATIONS

Several discussions were held with various CFMI and G.E. personnel concerning the vibrational characteristics of the F-108. The following paragraphs briefly present the information obtained.

The F-108 vibration specification was built on a two transducer format. One transducer was mounted permanently on the engine near the number 1 bearing. The second transducer was mounted on the turbine rear frame near the aft engine mount. The Lp (low speed shaft RPM) ranges from 20 to 85 Hertz and the

vibration data filter used over this range had a 2-Hertz bandwidth. The core RPM ranges over a frequency from 150 to 250 Hertz and was filtered similarly to the Lp signal. The acceptance data shipped with an engine was the maximum vibration response for both low and high speed shaft filters at both transducer locations. The response versus speed trace for both filters at both transducer locations were saved and available to the Air Force upon request but are not shipped with the engines. Trace data was reviewed for 19 engines during this program (see Subsection 6.3).

During the development stages of the F-108 vibration data was collected up to a frequency of 5000 Hertz without filters.

Typically, an F-108 engine will require some trim balance in the test cell. The test cell was the first and only time the entire rotor system was balanced as a unit. All trim balancing must be done on the low speed fan system due to the construction of the engine.

The engine had three predominate resonant modes which occur near 40, 60 and 75 Hertz. The modes most sensitive to imbalance are the 60- and 75-Hertz modes. Generally balancing corrections are required for these frequencies.

6.3 EVALUATION OF ACCEPTANCE RUN VIBRATION DATA FOR THE F-108

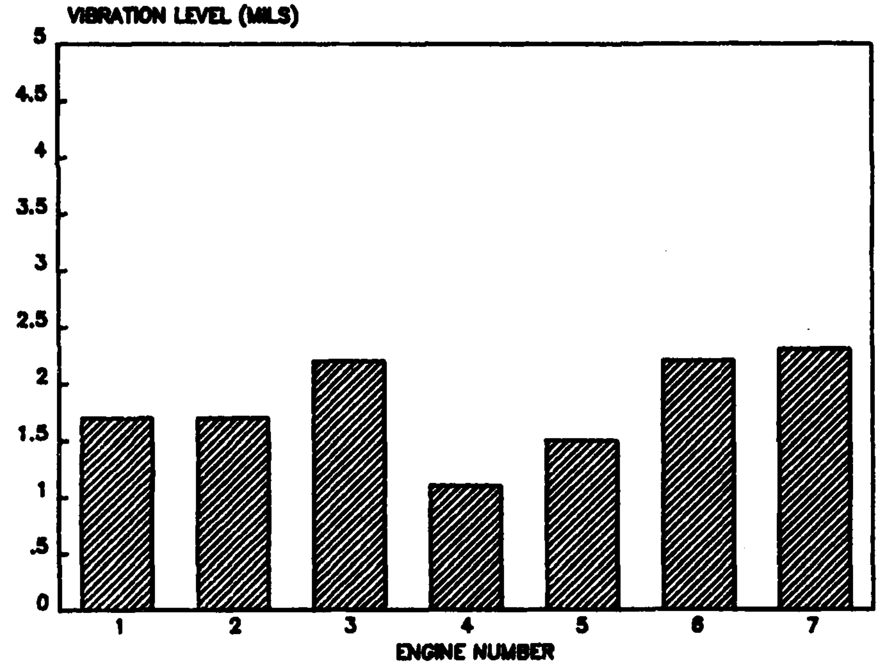
The objective during the review of the acceptance run vibration data was to determine if there was a relationship between the test cell vibration data and in-flight Rumble. A total of 117 engine data sets were reviewed of which 15 engines had been squawked for Rumble in flight.

The pertinent data for the 15 engines which have Rumble is given in Table 10. The vibration data presented in Table 10 were that which corresponds to the low speed spool. Figures 36 and 37 present plots of the vibration data from the number 1BRG and TRFV transducers respectively. About half of the Rumble engines show

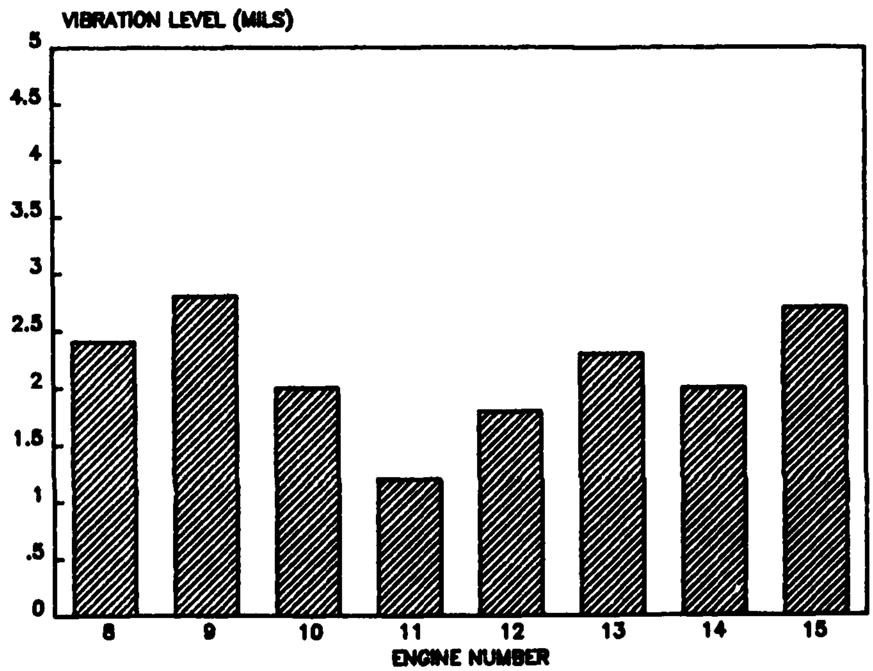
TABLE 10

RUMBLE ENGINE VIBRATION DATA

Engine #	#1BRG	TRFV	Date Balanced	Date Squawk	Time Between Balance & Squak (Months)	Engine Position
710-103	1.7	2.8	2/82	12/82	10	2
711-114	1.7	3.4	3/84	1/85	10	3
710-139	2.2	3.4	--	5/85	--	3 & 1
710-112	1.1	2.9	--	8/85	--	1
710-107	1.5	3.0	--	8/85	--	2
711-117	2.2	3.9	--	8/85	--	4
710-131	2.3	3.3	2/84	5/85	15	3
711-252	2.4	3.6	6/85	10/85	4	2
711-306	2.8	3.8	10/85	2/86	4	3
710-137	2.0	3.6	2/85	3/86	13	2
711-141	1.2	2.3	2/84	4/86	26	2
710-148	1.8	1.3	3/84	6/86	27	3
711-329	2.3	3.4	11/85	9/86	10	3
711-406	2.0	3.6	5/86	9/86	4	3
710-359	2.7	3.2	1/86	10/86	9	3

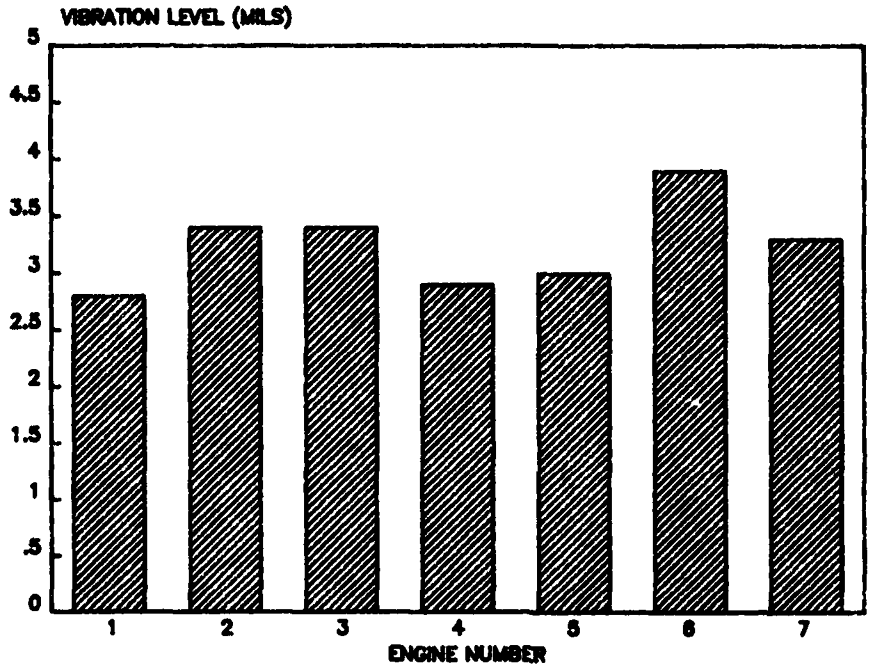


PLOT LABLE	ENGINE NUMBER
1	710-103
2	711-114
3	710-139
4	710-112
5	710-107
6	711-117
7	710-131

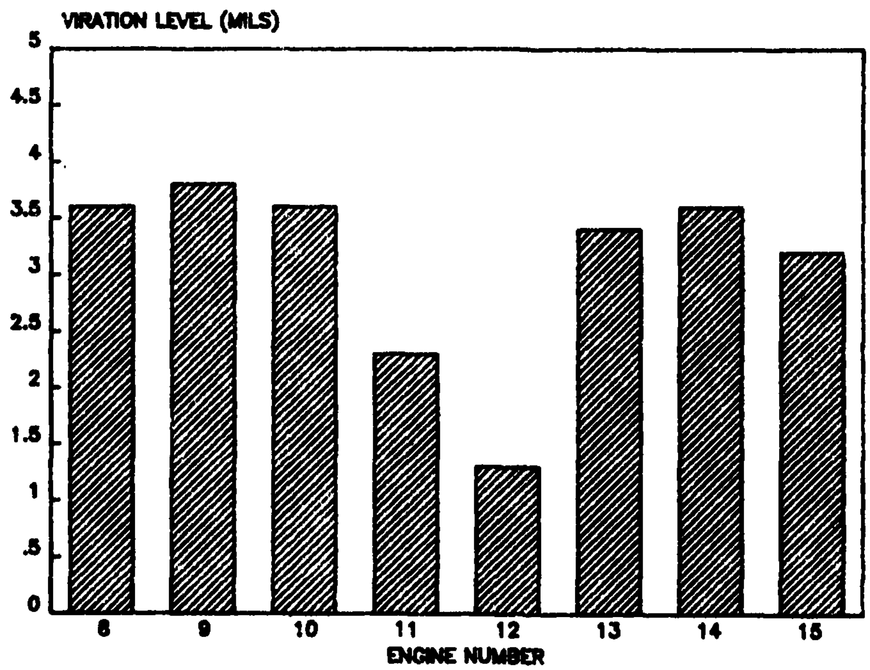


PLOT LABEL	ENGINE NUMBER
8	711-252
9	711-306
10	710-137
11	711-141
12	710-148
13	711-329
14	711-406
15	710-359

Figure 36. Vibration Response at Number 1 BRG for Engines With Rumble.



PLOT LABLE	ENGINE NUMBER
1	710–103
2	711–114
3	710–139
4	710–112
5	710–107
6	711–117
7	710–131



PLOT LABEL	ENGINE NUMBER
8	711–252
9	711–306
10	710–137
11	711–141
12	710–148
13	711–329
14	711–406
15	710–359

Figure 37. Vibration Response at TRFV For Engines With Rumble.

a vibration level above 2.0 at the number 1BRG. However, at the TRFV, 10 of the 15 engines have vibration above 3.0. It appears from this data that the TRFV transducer data might be helpful in identifying Rumble engines.

Closer review of the TRFV data reveals that the average of the Rumble engines vibration response was 3.17. The average for the 102 engines for which no Rumble has been reported was 2.59. Only 32 out of the 102 engines (31.4 percent) which have not been reported for Rumble had vibration responses over 3.0. As stated above, 66.7 percent of the Rumble engines had vibration levels in the test cell above 3.0.

Out of the 15 Rumble engines, 11 engines had dates which indicated when the acceptance run vibration data were collected. Eight of these 11 engines had vibration levels over 3.0 while the other 3 engines had vibration levels under 3.0. The average time from the acceptance run to in-flight squawk for the engines with vibration levels over 3.0 was 8.63 months. The average time from the engines with vibration levels under 3.0 was 21 months. It would be reasonable to assume that the engine balance force; i.e., engine vibration level, would grow with time. It is therefore quite conceivable that the vibration levels of the 3 engines which had test cell vibrations under 3.0 had grown to over 3.0 before Rumble occurred.

One more case can be developed to evaluate the connection between engine vibration level and Rumble by studying the history of Engine 711-252. The history for engine 711-252 has been recorded as:

- June 1985 - Acceptance test vibration level 3.6.
- October 1985 - Squawk in flight Rumble.
- November 1985 - Squawk in flight Rumble.
- December 1985-March 1986 - Engine pulled sent back to CFMI.

- April 1986 - Engine test cell vibration level 5.8 (Strother)
- May 1986 - Acceptance test vibration level 2.0 (Strother)

Since May 1986 there has been no reported Rumble from Engine 711-252.

Based on the data evaluated, it would appear that the reduction of the vibration acceptance specification from 4.0 mils to 3.0 mils would reduce the occurrence of Rumble. Noted that the conclusion is based on the limited amount of data reviewed. Before the acceptance specification is changed, the following efforts should be completed:

- A complete review and evaluation of the vibration data for all F-108 engines in service.
- A more stringent requirement that pilots report Rumble events so that all engines which Rumble can be identified.
- Comparison of the data from the above two tasks similar to what was done on this program.

If the above tasks result in the same conclusion as this effort, then

- A complete evaluation of the cost impact on the purchase price and overhaul costs resulting from reducing the vibration acceptance levels.

7.0 POSSIBLE RUMBLE SOLUTIONS

The cause of Rumble was the vibration coming from the engine. This vibration was transmitted through the nacelle, wing, and fuselage structure and was amplified by resonants in these structures. The Rumble was sensed both from the change in the acoustic conditions in the cabin and from the change in the vibrations felt in the cabin.

The development and evaluation of solutions to Rumble are presented in three specific categories which are:

(1) Solutions applicable to the engine.

(2) Solutions applicable to the nacelle/wing structure.

(3) solutions applicable to the fuselage.

7.1 ENGINE SOLUTIONS TO RUMBLE

The engine was providing the driving force for Rumble. If we can reduce the driving force, i.e., the engine vibration levels, then Rumble will be eliminated at the source. This approach cures the problem; it does not merely hide the symptoms.

One method to reduce the driving force would be to reduce the vibration acceptance levels for the engine. The full ramifications of reducing the vibration specifications are not known. However, based on the data and analysis presented in Subsection 6.3, it appears that a significant reduction in the number of Rumble events would occur if the overall vibration level for the low speed shaft frequencies would be reduced to 3.0. Additional studies are required before the total advantages and disadvantages of this solution can be defined.

In the F-108 engine, there were structural resonances which amplify the out-of-balance forces generated by the engine. Another solution to reduce the forces causing Rumble would be to

redesign the engine structure such that there would be no engine structural resonant frequencies in the range of interest.

Although this task is theoretically possible, practically it is impossible for two reasons. First, the design of an engine system which has no overall engine resonant frequencies in the 20- to 80-Hertz range and meets other performance requirements such as total engine weight is impossible. Secondly, the cost to attempt such an effort would be at least 50 to 75 percent of the cost to design a new engine. Such a cost is not acceptable to eliminate a nuisance type problem.

The third way to reduce the Rumble driving forces would be to reduce the resonant amplification caused by the engine structural resonances which can be accomplished by adding damping to the engine system. Overall engine modes are typically inherently highly damped which means simply that these modes are already highly damped and adding damping to such systems would be very difficult. Damping could be added but there would be a weight penalty of 10 to 30 percent of the weight of the engine required. An additional concern would be the shape change to the engine envelope which would be required to accommodate the damping.

The most practical way of reducing the Rumble driving forces would be to simply change the engine speed which changes the imbalance force frequency. The change in frequency eliminates the structural resonant amplification and thereby eliminates Rumble.

7.2 NACELLE/WING STRUCTURE SOLUTIONS TO RUMBLE

If it is impossible to cure Rumble at the source (the engine) then an alternative approach would be to cure the symptoms. One such approach would be to reduce the force transmitted from the engine through the nacelle/wing structure.

The modal analysis (see Subsection 4.2) revealed that the nacelle/wing structure with the engine installed had resonant frequencies in the frequency range of Rumble which would amplify the vibration forces coming from the engine. Therefore, one way to reduce the forces driving Rumble in the cabin would be to eliminate these structural resonances. A redesign of the nacelle/wing structure would be impractical because the cost would compare to the cost of the "A" to "R" conversion which was 13 million dollars for the redesign and 7.2 million dollars per aircraft for modification kits and installation charges. Realistically, there would be little hope of designing a nacelle/wing structure which would meet the weight and aerodynamic requirements and not have system resonances in the 20- to 80-Hertz range.

The second approach to reduce the force transmitted would be to add damping to the structure. This approach would be impractical because of the installation costs and the weight penalty resulting from adding the damping, estimated at 100 to 1000 pounds of damping required per engine nacelle to reduce Rumble.

7.3 FUSELAGE SOLUTIONS TO RUMBLE

Any Rumble solution applied to the fuselage would accomplish the reduction of Rumble by the elimination of the noise radiators and structural vibrators. One immediate problem with a fuselage solution to Rumble, pointed out in Subsection 4.1, would be that the entire crew and cargo area would be treated since there was no single resonator.

The solutions available for the fuselage to solve Rumble are:

(1) Structural redesign to eliminate structural resonances.

(2) Add damping to reduce resonant response.

(3) Add acoustic absorption materials to reduce noise levels.

The structural redesign option would be impractical from the standpoint of cost and time required to implement the modification.

Adding either the damping or the acoustic treatments would be impractical for several reasons. The weight penalty and basic treatment costs would be high. The most cost effective way to incorporate this addition would be as a standard PDM procedure. Due to the long time period between PDM's on the KC-135, it would take a significant amount of time to outfit the fleet with the required treatment. Another disadvantage of the acoustic treatment would be its hindrance of normal Air Force inspection of various fuselage components.

REFERENCES

1. Harris, C. M., and Charles E. Crede, Shock and Vibration Handbook, McGraw-Hill Book company, 1976, pp. 44-23, Fig. 44-20.

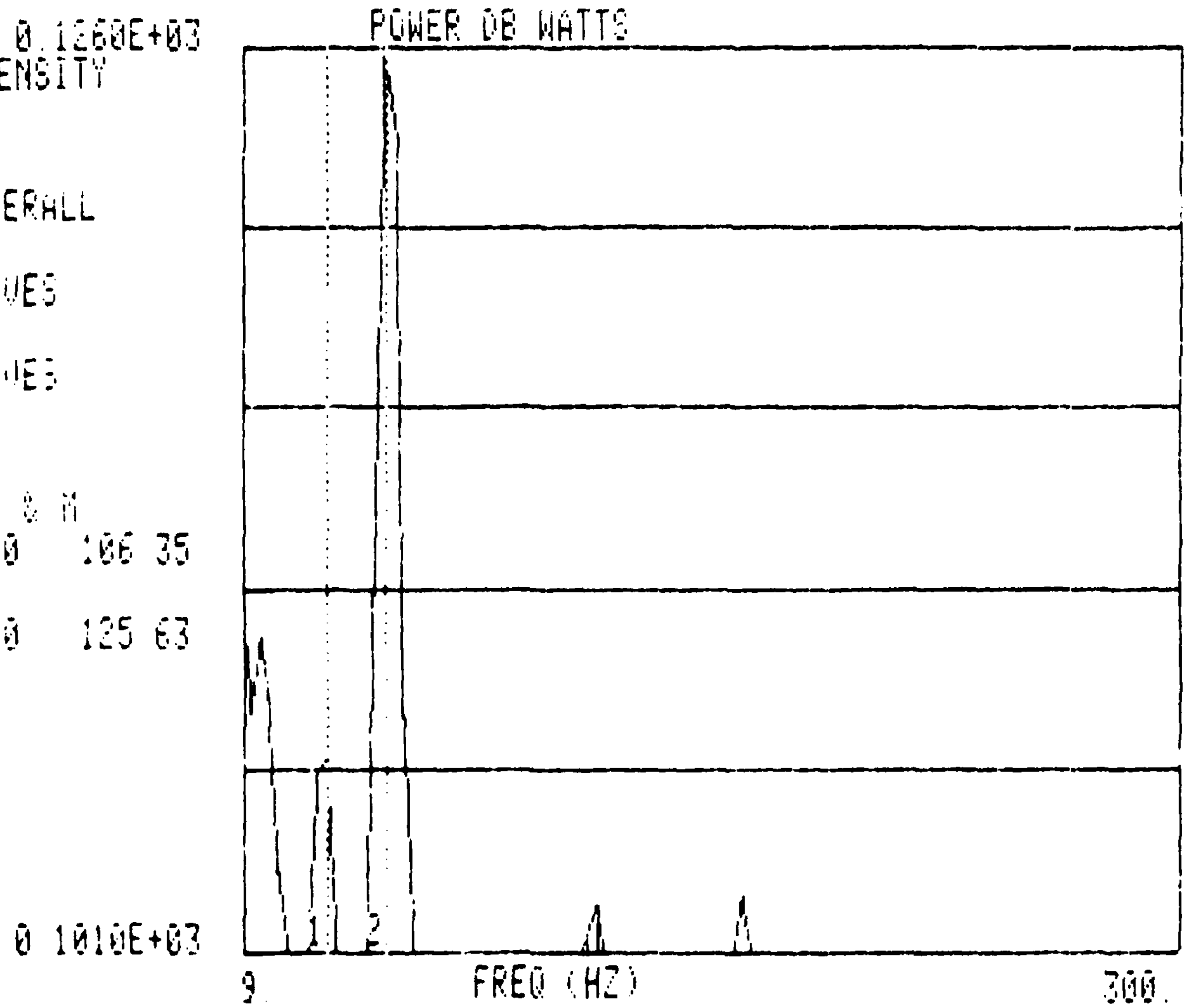
APPENDIX A

DATA POINTS FOR FIRST FLIGHT

TEST1

FREQ= 9.000
MAG= 110.39

P#1

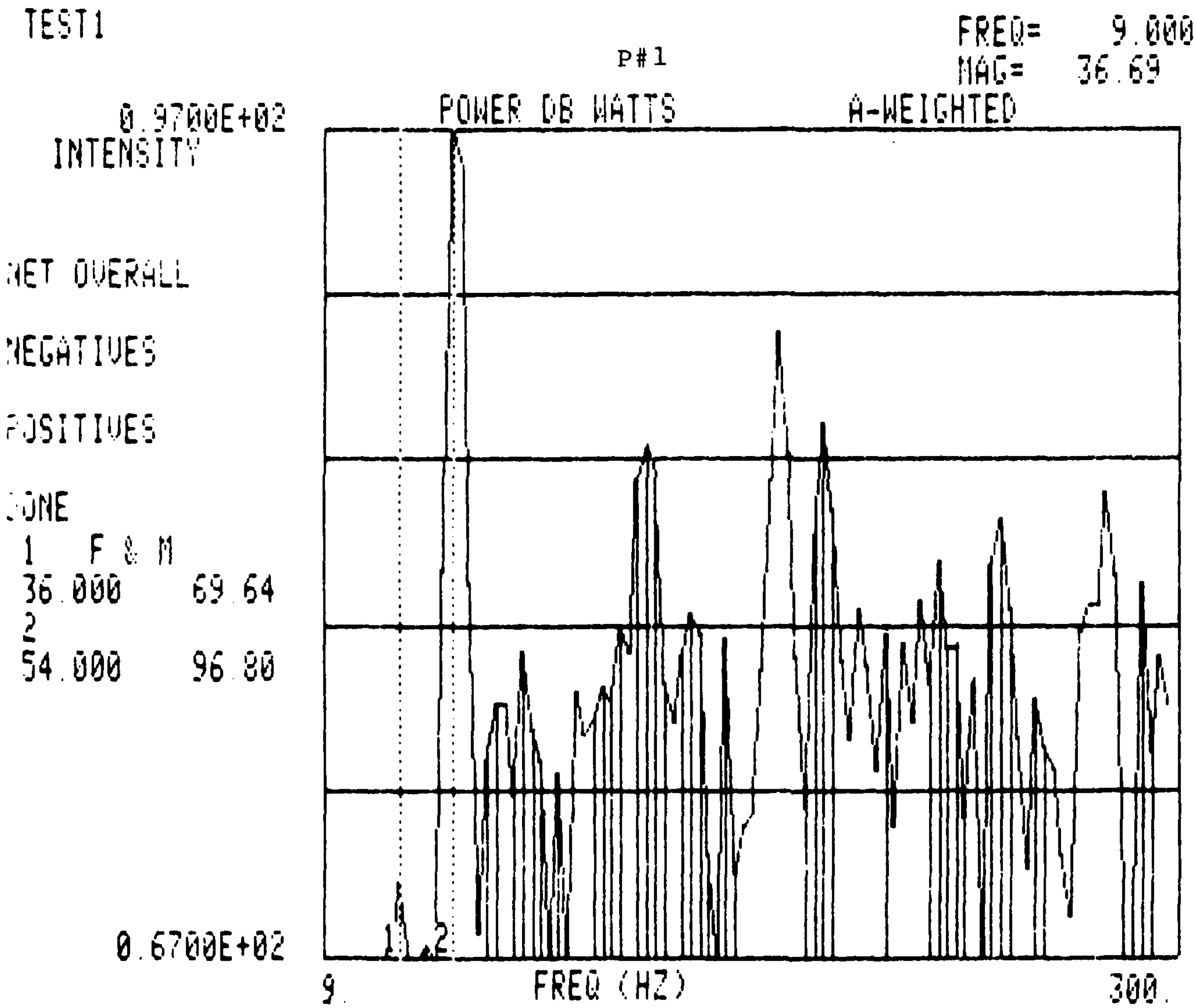


NET OVERALL

NEGATIVES

POSITIVES

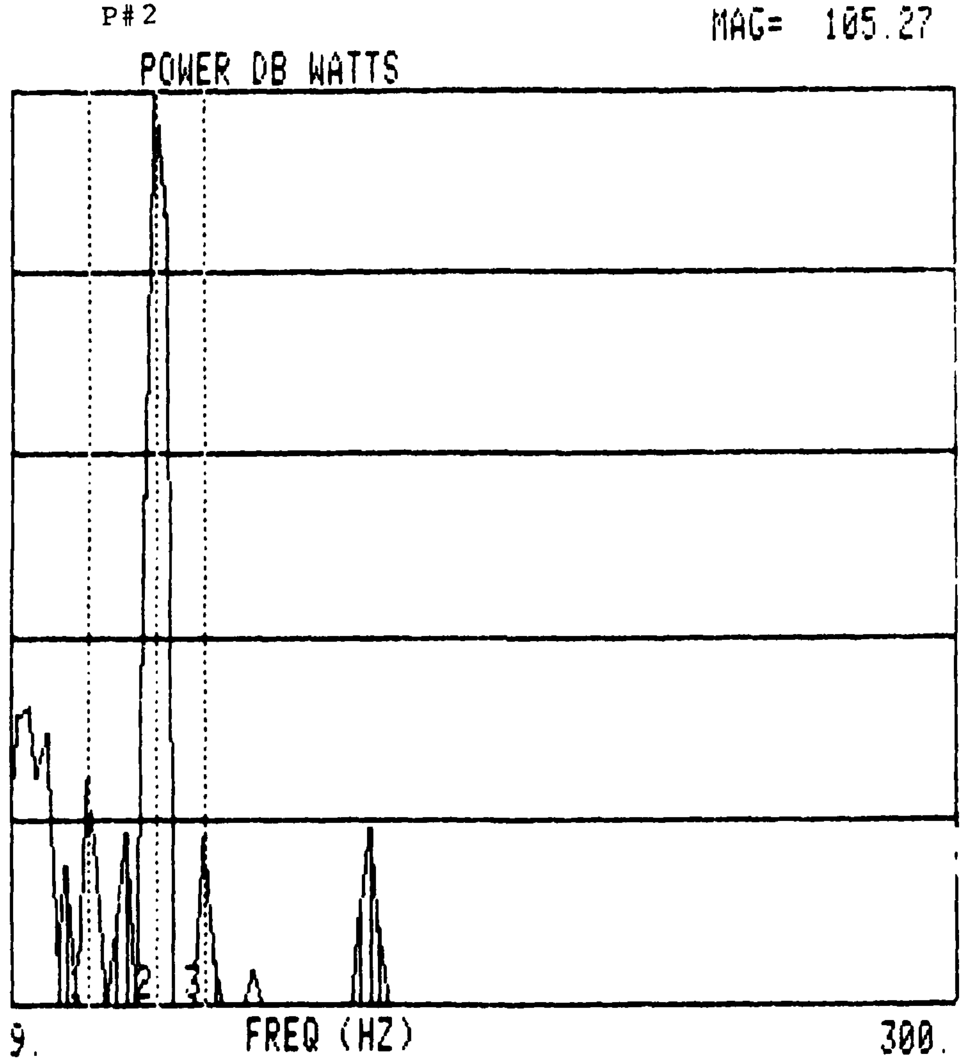
DONE
1 F & M
36.000 106 35
2
54 000 125 63


TEST1
P#1
FREQ= 9.000
MAG= 36.69
0.9700E+02
INTENSITY
POWER DB WATTS
A-WEIGHTED
NET OVERALL
NEGATIVES
POSITIVES
ZONE
1 F & M
36.000 69.64
2
54.000 96.80
0.6700E+02
9.
FREQ (HZ)
300.

TEST1

FREQ= 9.000
MAG= 105.27

0.1250E+03
INTENSITY



NET OVERALL

NEGATIVES

POSITIVES

DONE

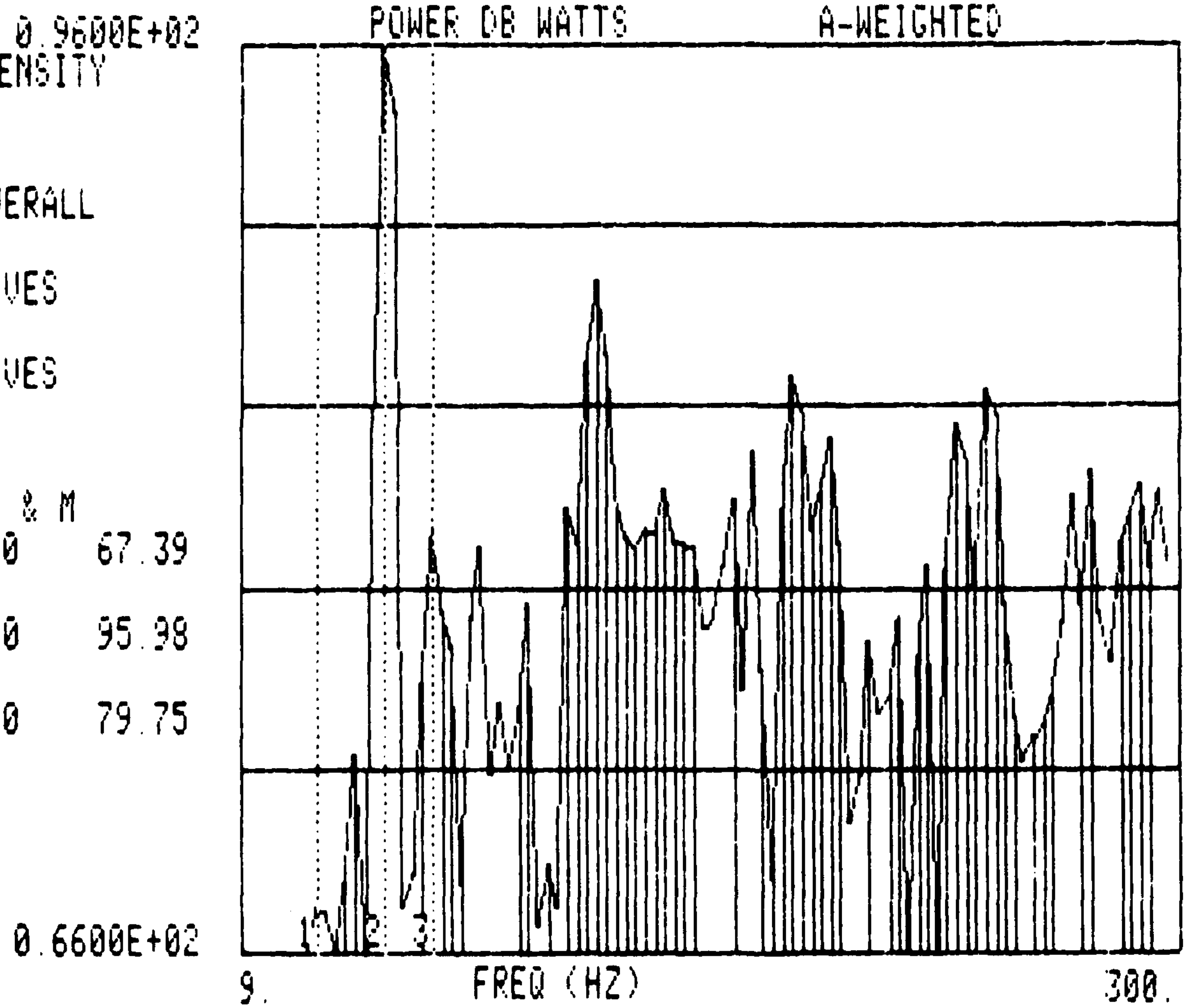
1	F & M	
	33.000	105.95
2		
	54.000	124.81
3		
	69.000	104.40

0.1000E+03

TEST1

P#2

FREQ= 9.000
MAG= 31.57



> NET OVERALL

NEGATIVES

POSITIVES

DONE

1	F & M
33.000	67.39
2	
54.000	95.98
3	
69.000	79.75

TEST1

FREQ= 9.000
MAG= 86.86

0.1270E+03
INTENSITY

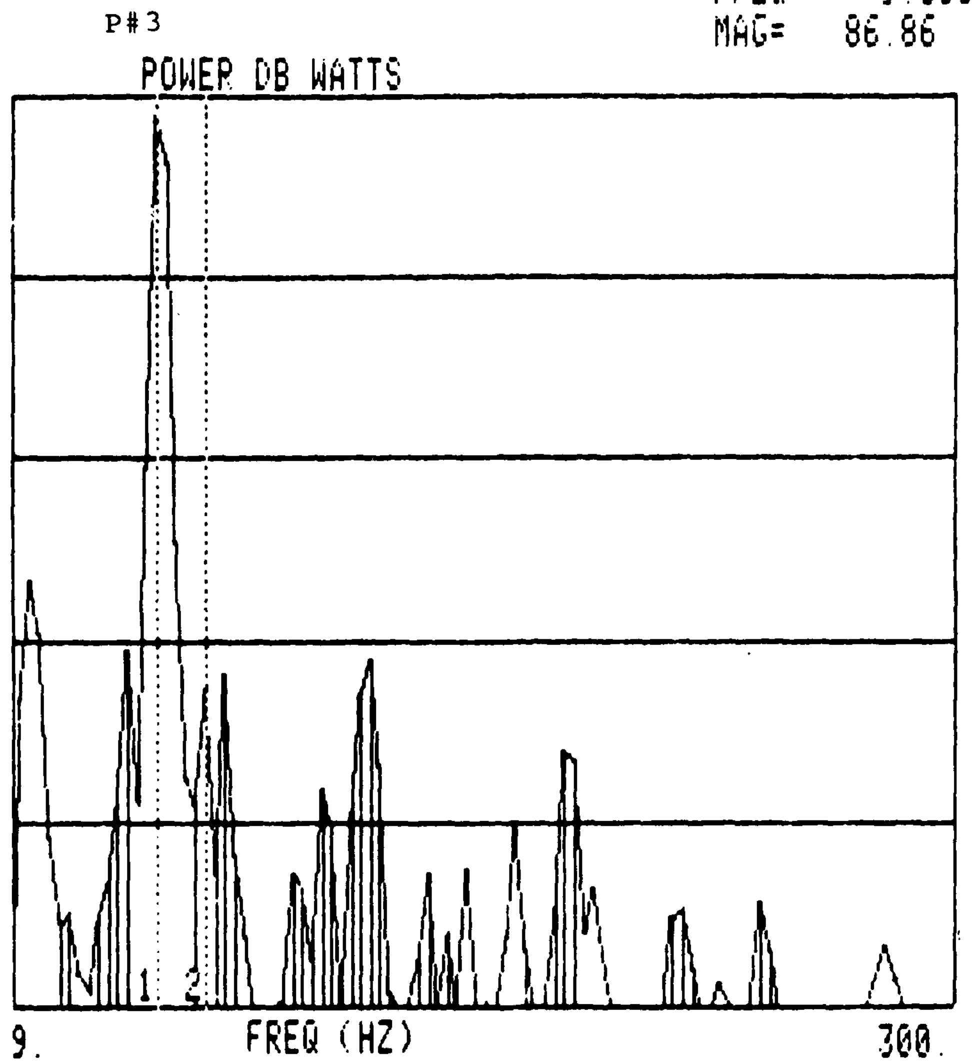
> NET OVERALL

NEGATIVES

POSITIVES

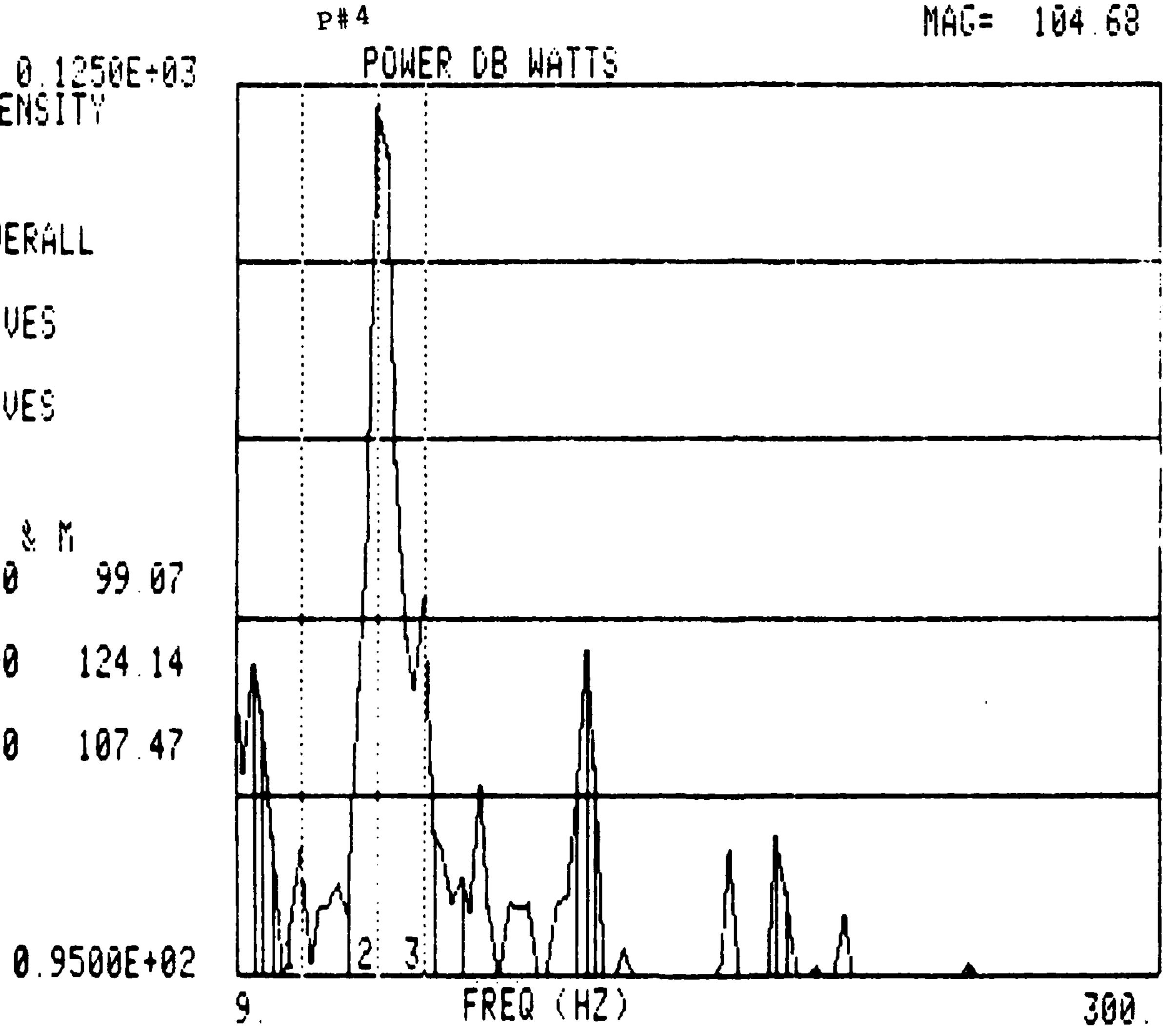
DONE
1 F & M
54.000 126.18
2
69.000 104.04

0.9200E+02



TEST1

FREQ= 9.000
MAG= 104.68



> NET OVERALL

NEGATIVES

POSITIVES

DONE

1 F & M
30.000 99.07
2
54.000 124.14
3
69.000 107.47

TEST1

FREQ= 9.000
MAG= 104.89

0.1240E+03
INTENSITY

> NET OVERALL

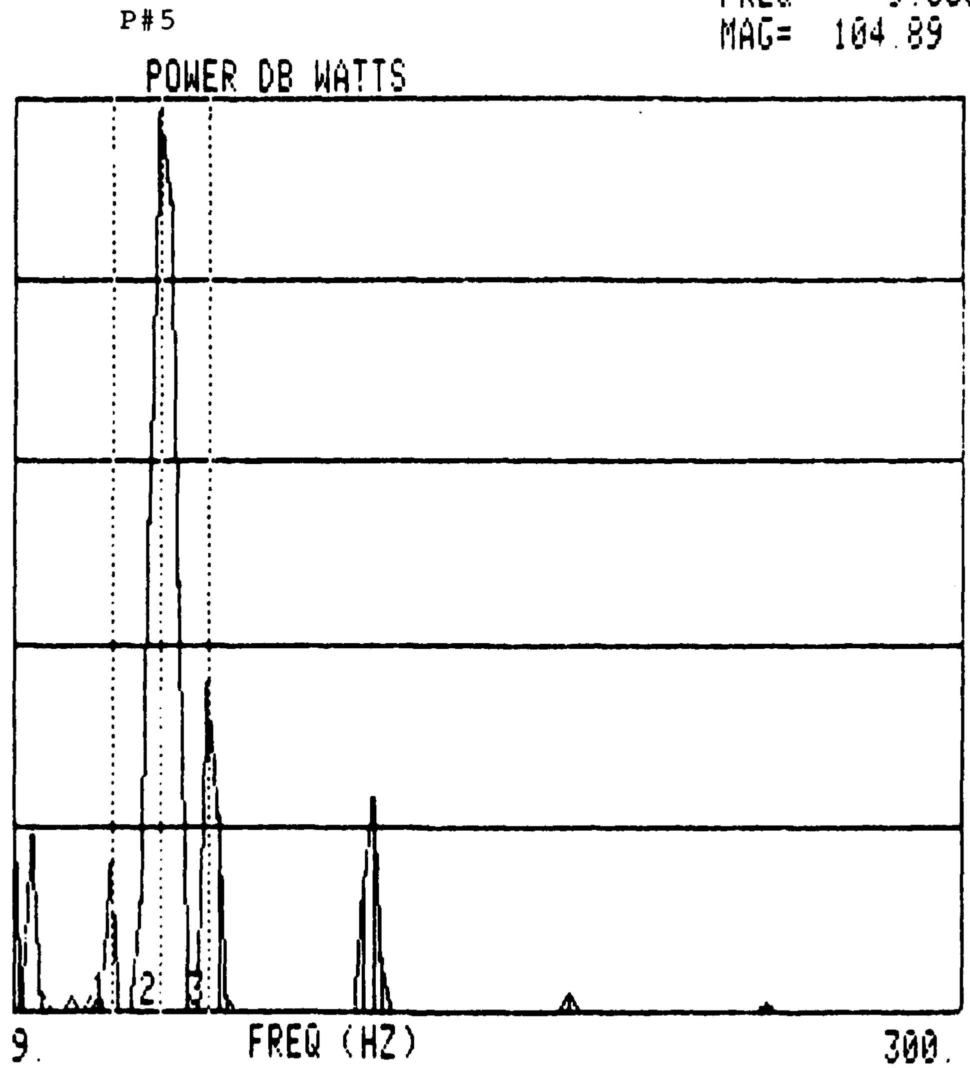
NEGATIVES

POSITIVES

DONE

1 F & M
39.000 102.89
2
54.000 123.50
3
69.000 107.80

0.9900E+02



TEST1

0.1230E+03
INTENSITY

> NET OVERALL

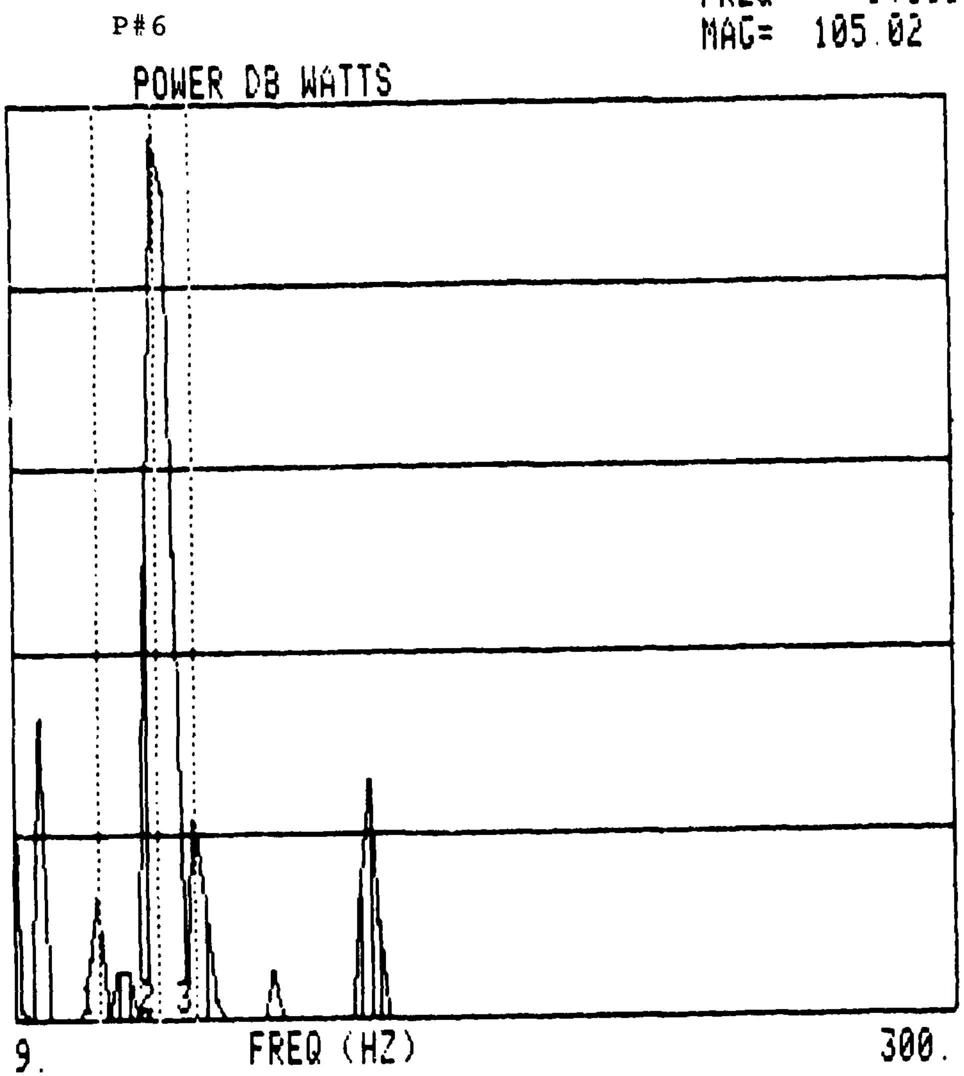
NEGATIVES

POSITIVES

DONE

1 F & M
36.000 101.26
2
54.000 122.06
3
66.000 103.35

0.9800E+02

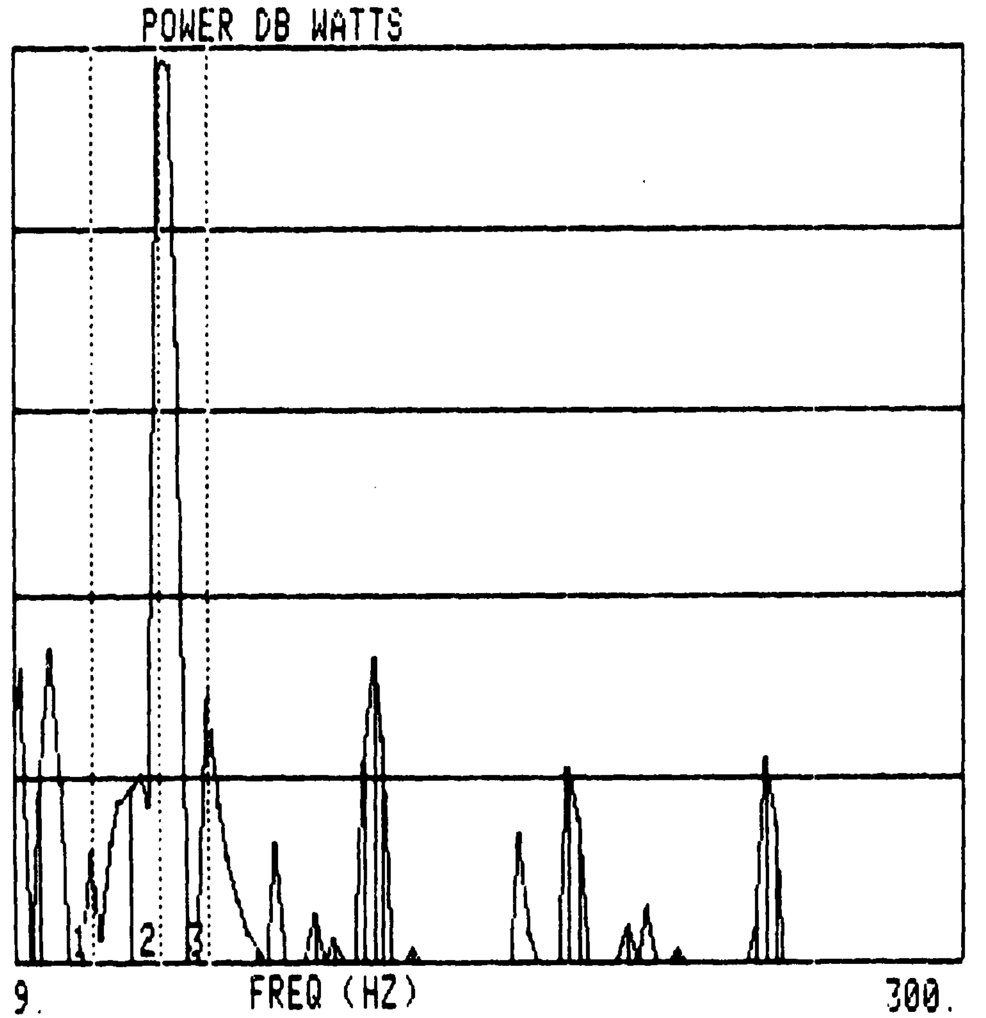


TEST1

P#7

FREQ=   9.000
MAG= 100.64

0.1230E+03
INTENSITY



> NET OVERALL

NEGATIVES

POSITIVES

DONE

1	F & M
33.000	96.35
2	
54.000	122.49
3	
69.000	101.35

0.9300E+02

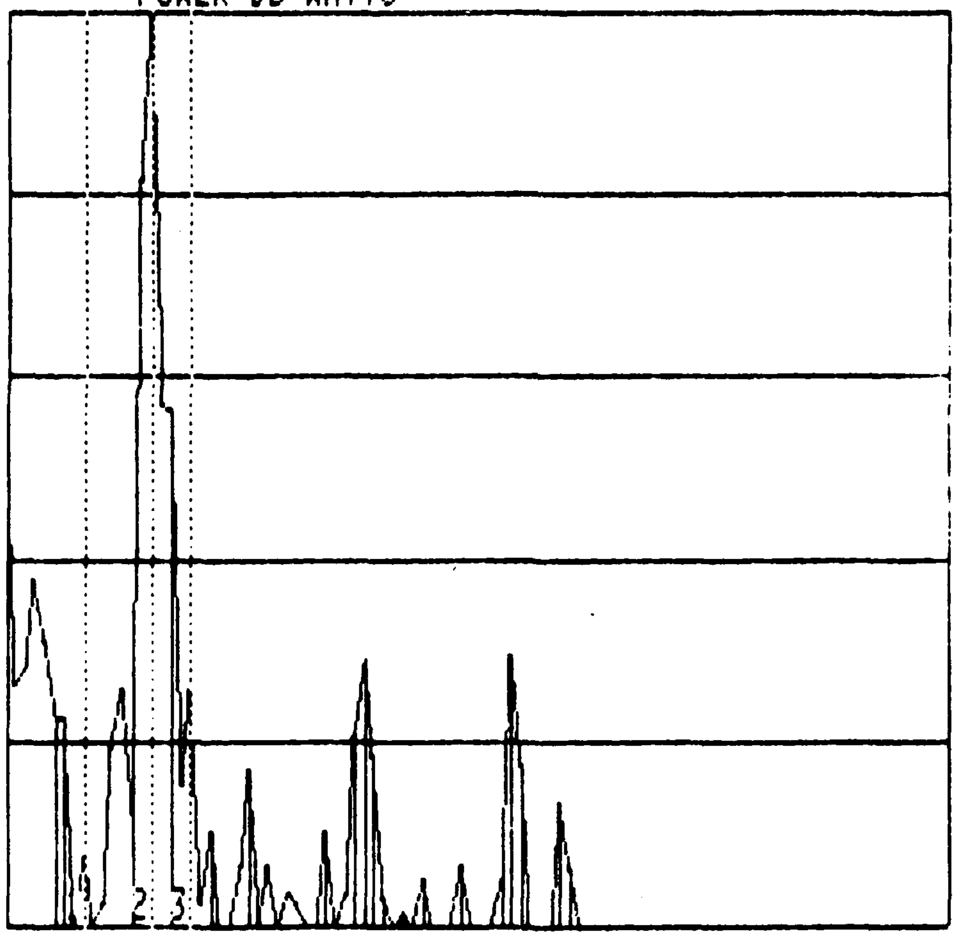
TEST1

P#8

FREQ= 9.000
MAG= 110.03

POWER DB WATTS

0.1280E+03
INTENSITY



0.9300E+02

9. FREQ (HZ) 300.

> NET OVERALL

NEGATIVES

POSITIVES

DONE

1 F & M
33.000 95.73
2
54.000 127.69
3
66.000 101.95

TEST1

FREQ= 9.000
MAG= 98.89

0.1140E+03
INTENSITY

> NET OVERALL

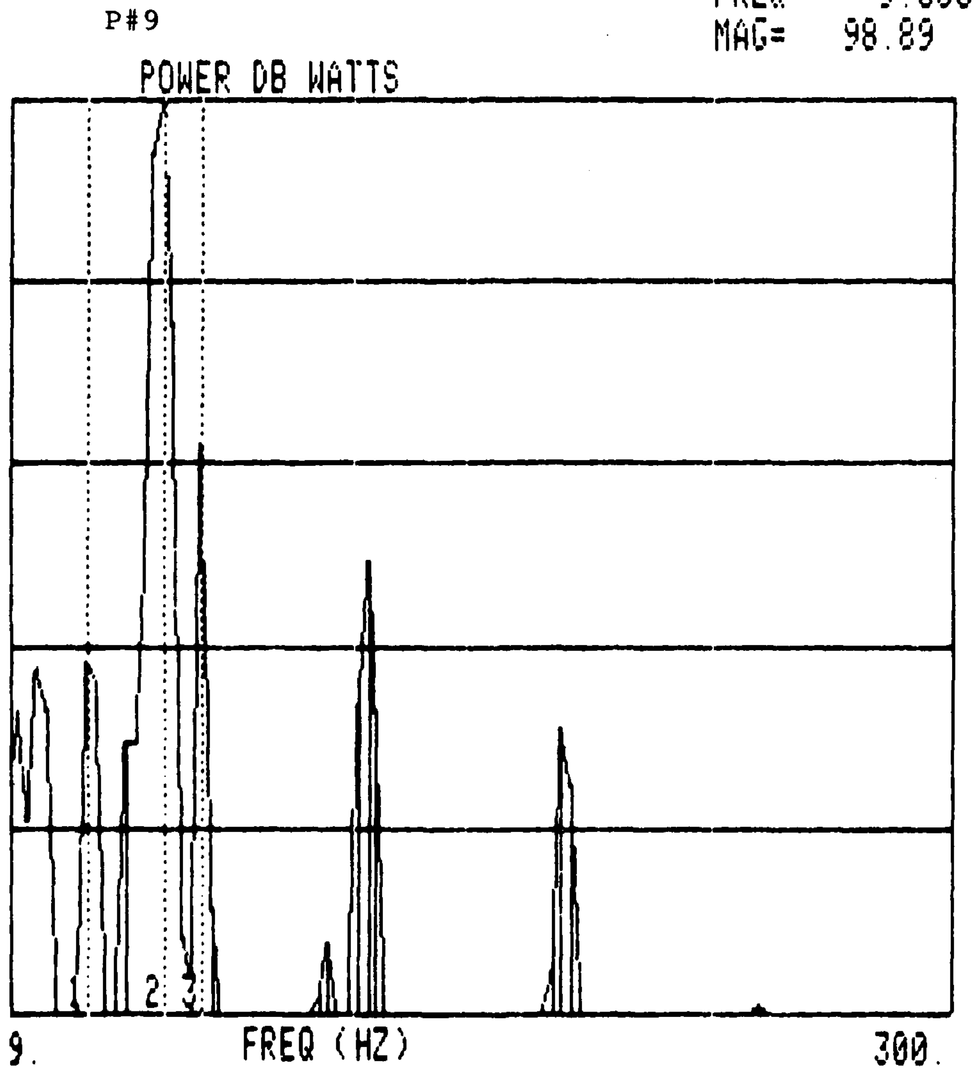
NEGATIVES

POSITIVES

DONE

1 F & M
33.000 101.52
2
57.000 113.88
3
69.000 106.35

0.9400E+02



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AFWAL-TR-88-4260 F33615-85-C-5040

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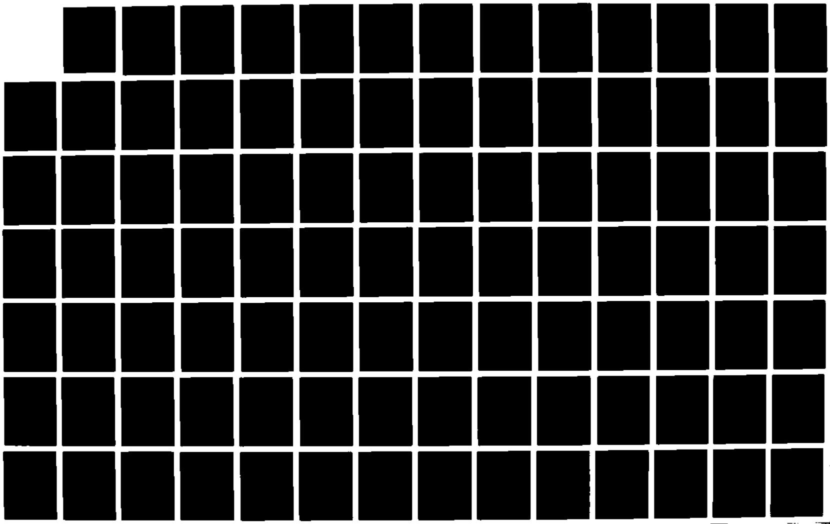
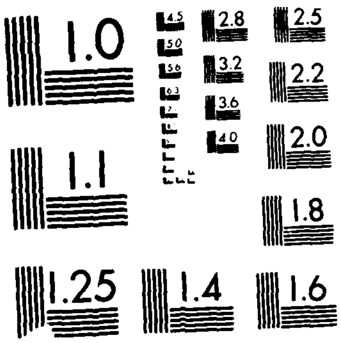


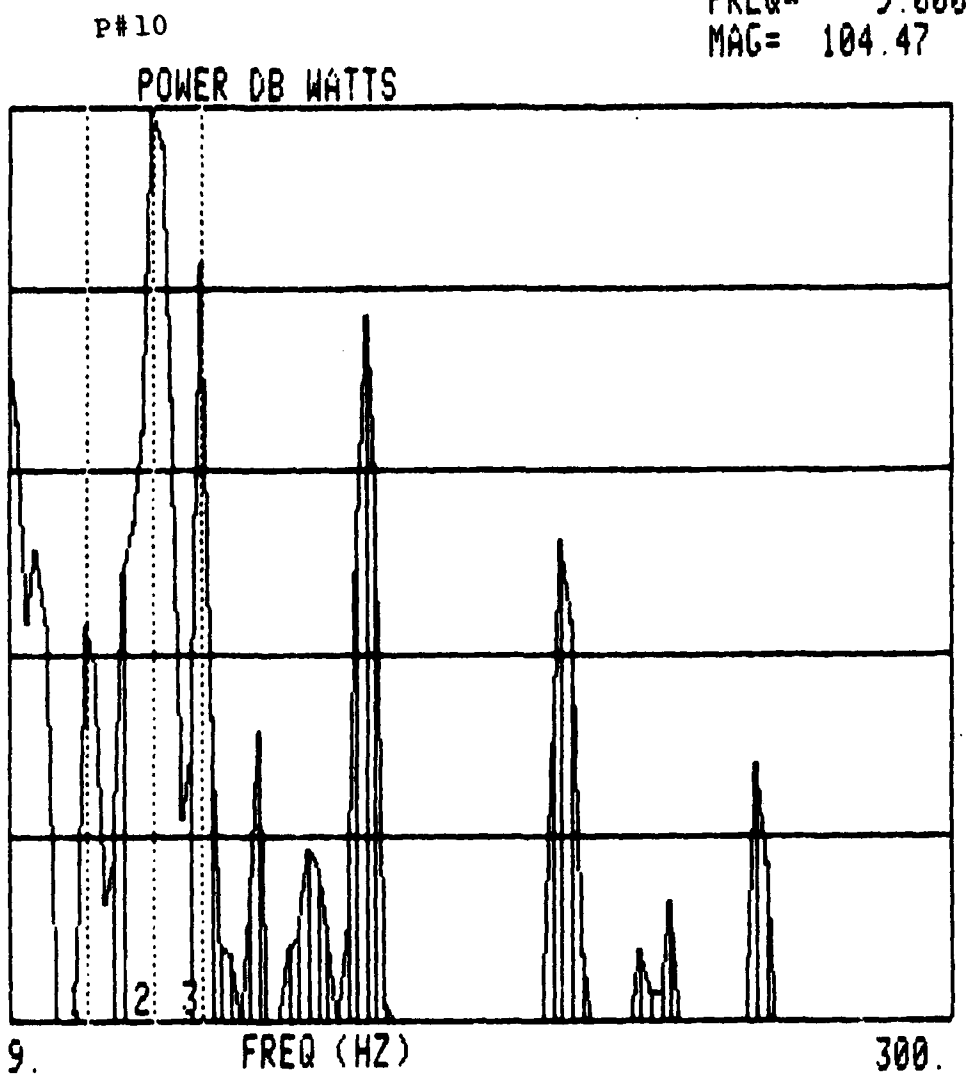


UTION TEST CHART

TEST1

FREQ= 9.000
MAG= 104.47

0.1100E+03
INTENSITY



0.9000E+02

> NET OVERALL

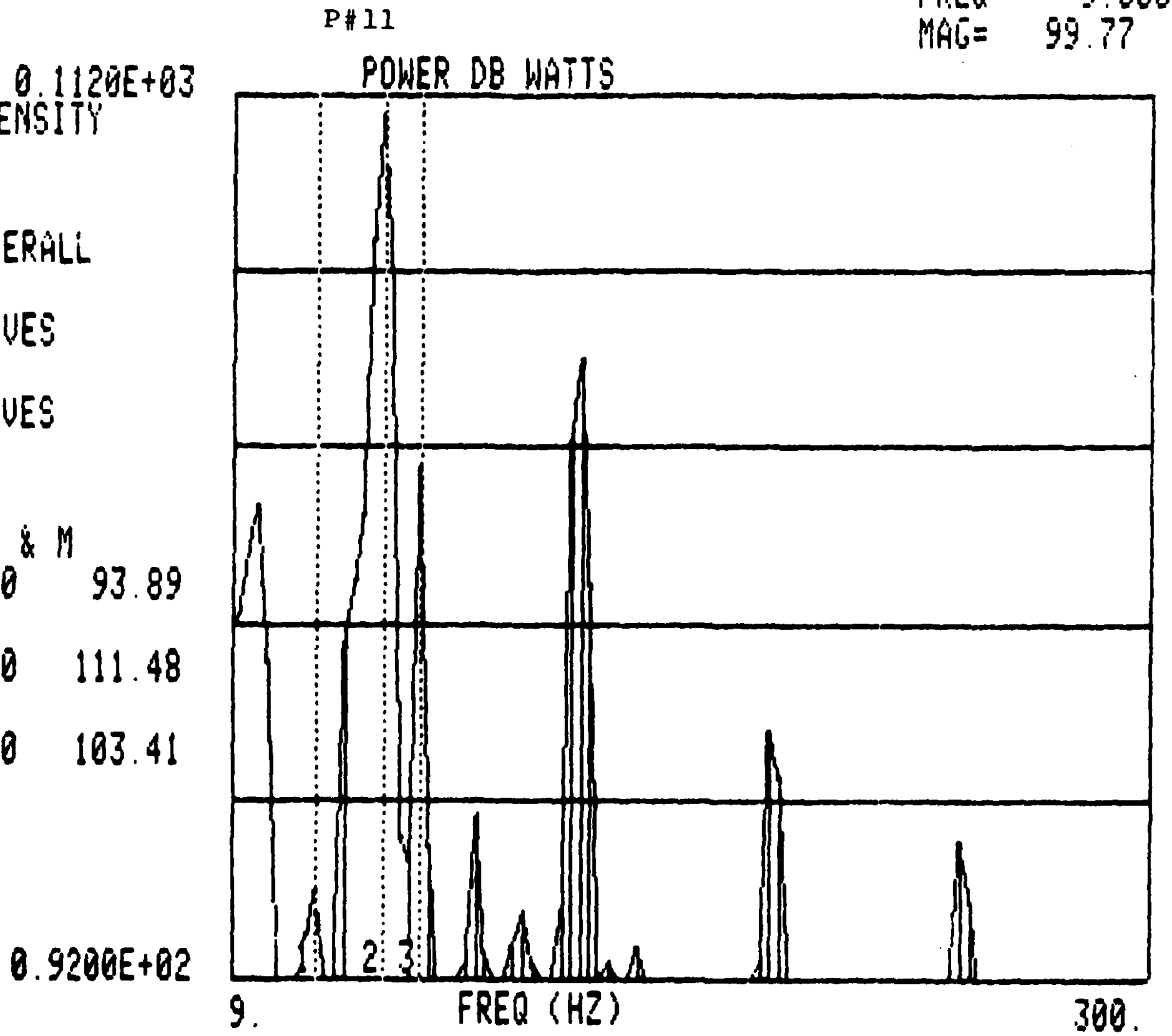
NEGATIVES

POSITIVES

DONE
1 F & M
33.000 98.51
2
54.000 109.77
3
69.000 106.45

TEST1

FREQ= 9.000
MAG= 99.77



\> NET OVERALL

NEGATIVES

POSITIVES

DONE

1	F & M	
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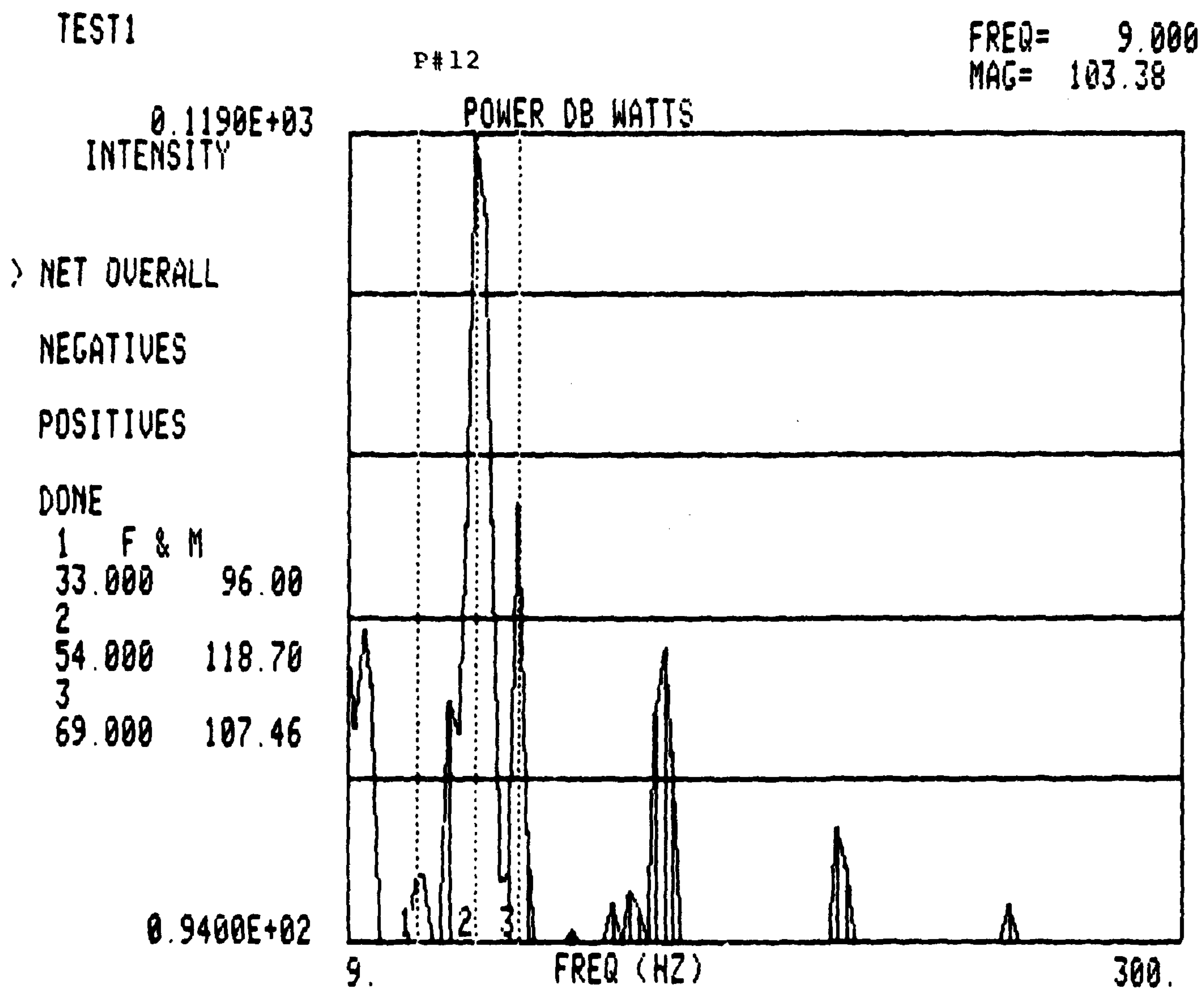
2		
	57.000	111.48
3		
	69.000	103.41


TEST1
P#12
FREQ= 9.000
MAG= 103.38
0.1190E+03
INTENSITY
POWER DB WATTS
) NET OVERALL
NEGATIVES
POSITIVES
DONE
1 F & M
33.000 96.00
2
54.000 118.70
3
69.000 107.46
0.9400E+02
1
2
3
9.
FREQ (HZ)
300.

TEST1

P#13

FREQ= 9.000
MAG= 106.61

POWER DB WATTS

0.1260E+03
INTENSITY

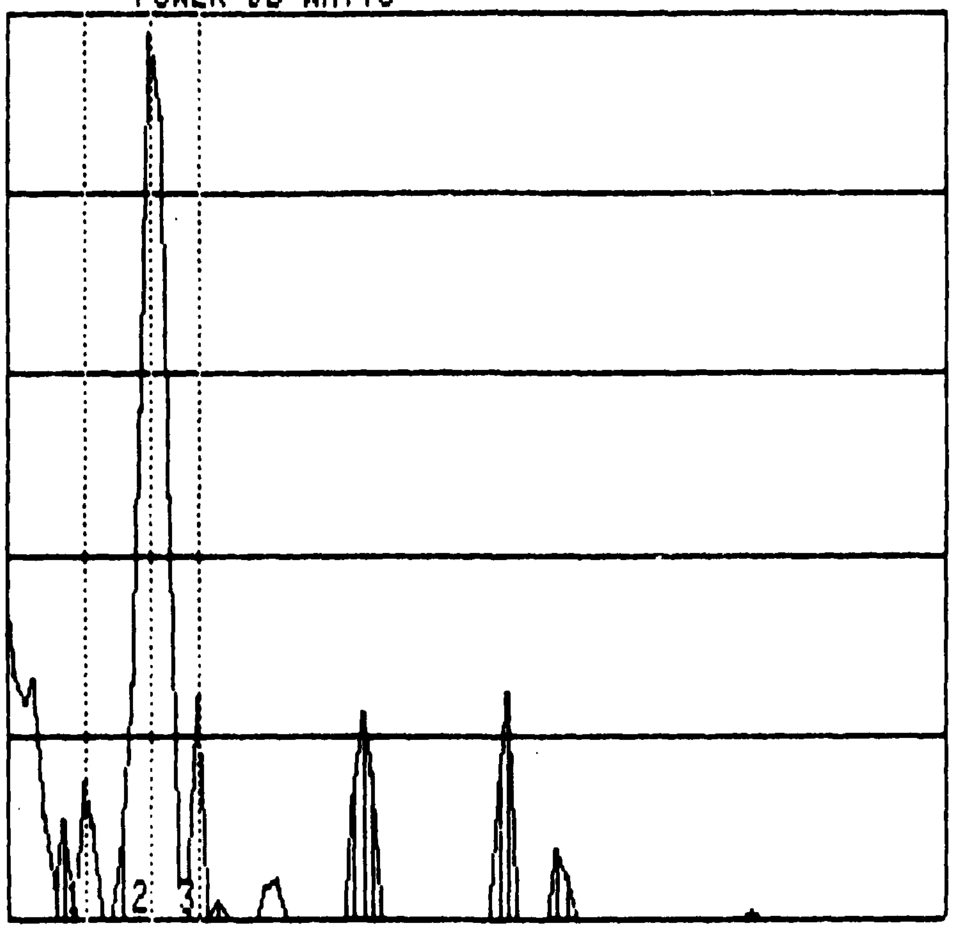
> NET OVERALL

NEGATIVES

POSITIVES

DONE
1 F & M
33.000 100.33
2
54.000 125.09
3
69 000 103.18

0.9600E+02



9. FREQ (HZ) 300.

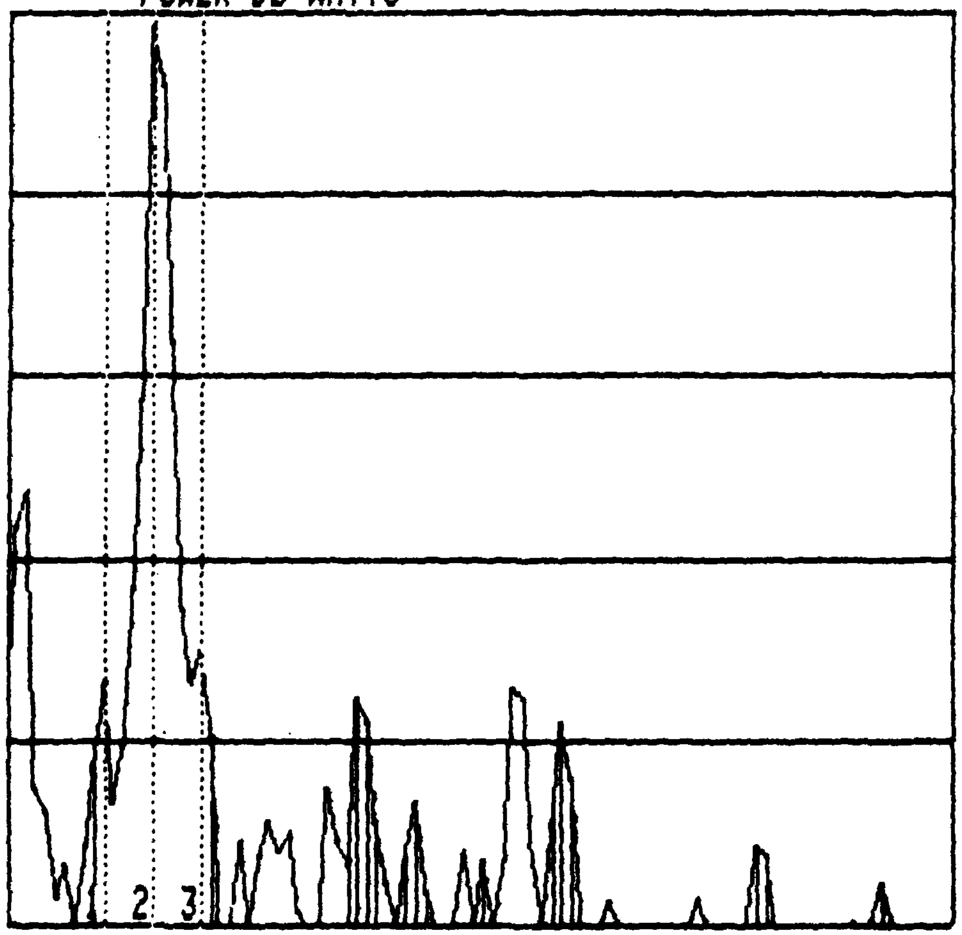
TEST1

FREQ= 9.000
MAG= 100.34

P#14

POWER DB WATTS

0.1270E+03
INTENSITY



0.9200E+02

9. FREQ (HZ) 300.

> NET OVERALL

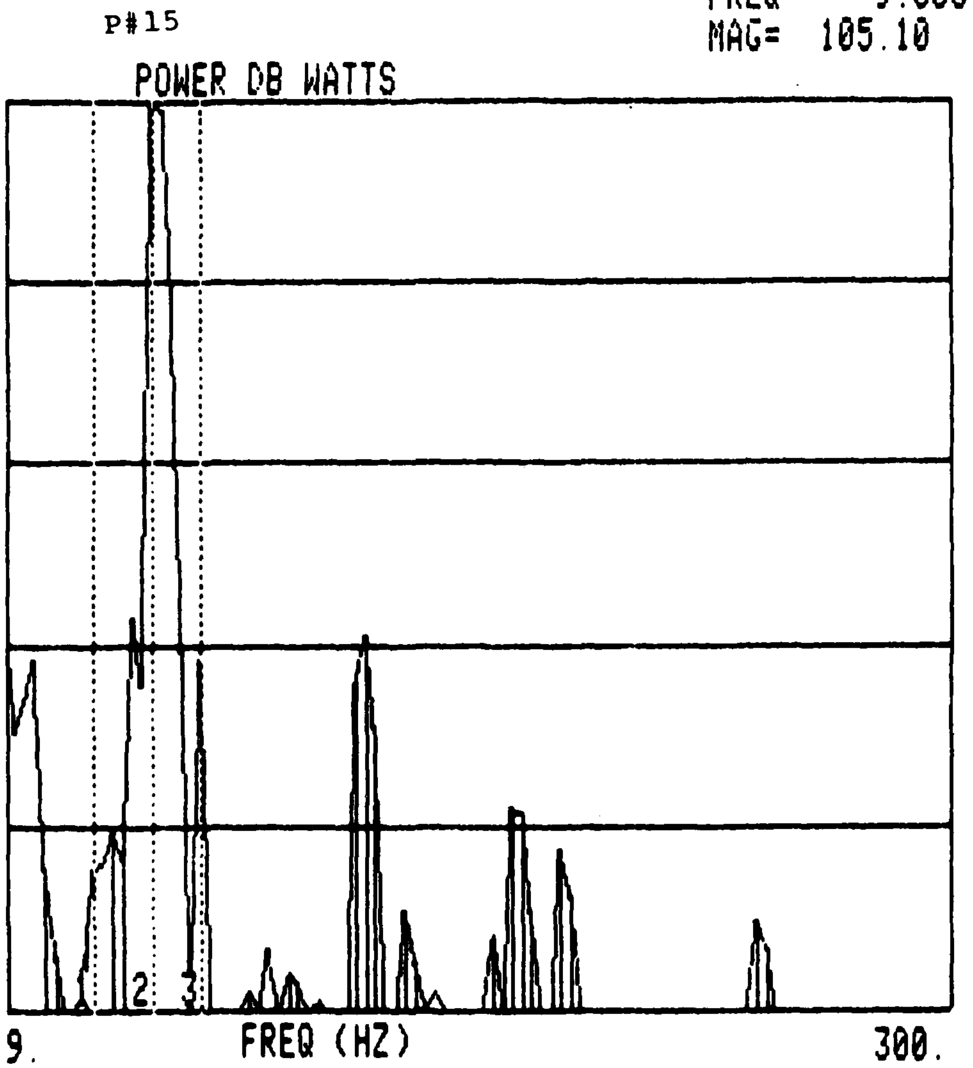
NEGATIVES

POSITIVES

DONE

1	F & M	
	39.000	101.25
2		
	54.000	126.36
3		
	69.000	102.54

TEST1



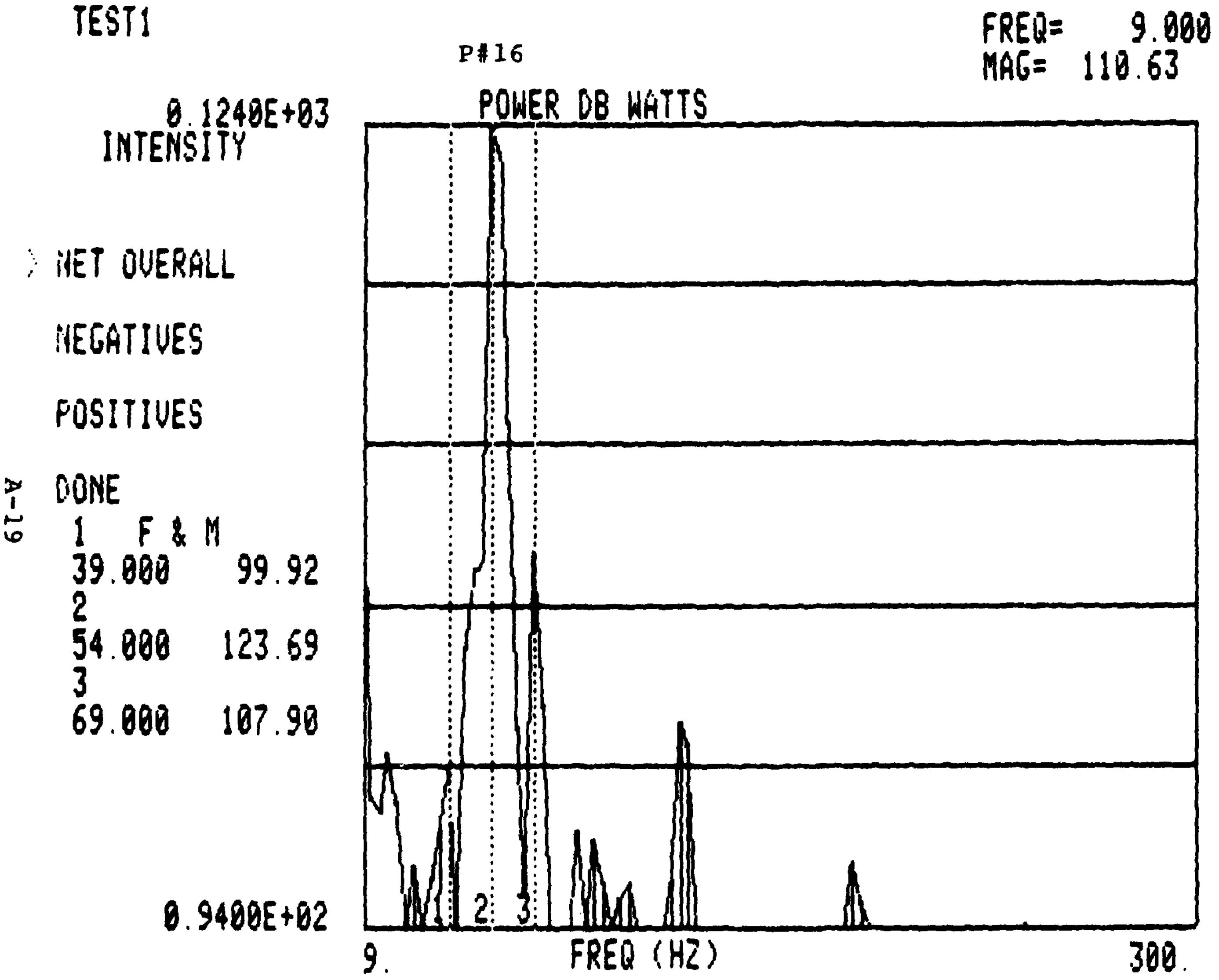
> NET OVERALL

NEGATIVES

POSITIVES

DONE

1	F & M
36.000	97.57
2	
54.000	122.96
3	
69.000	104.36

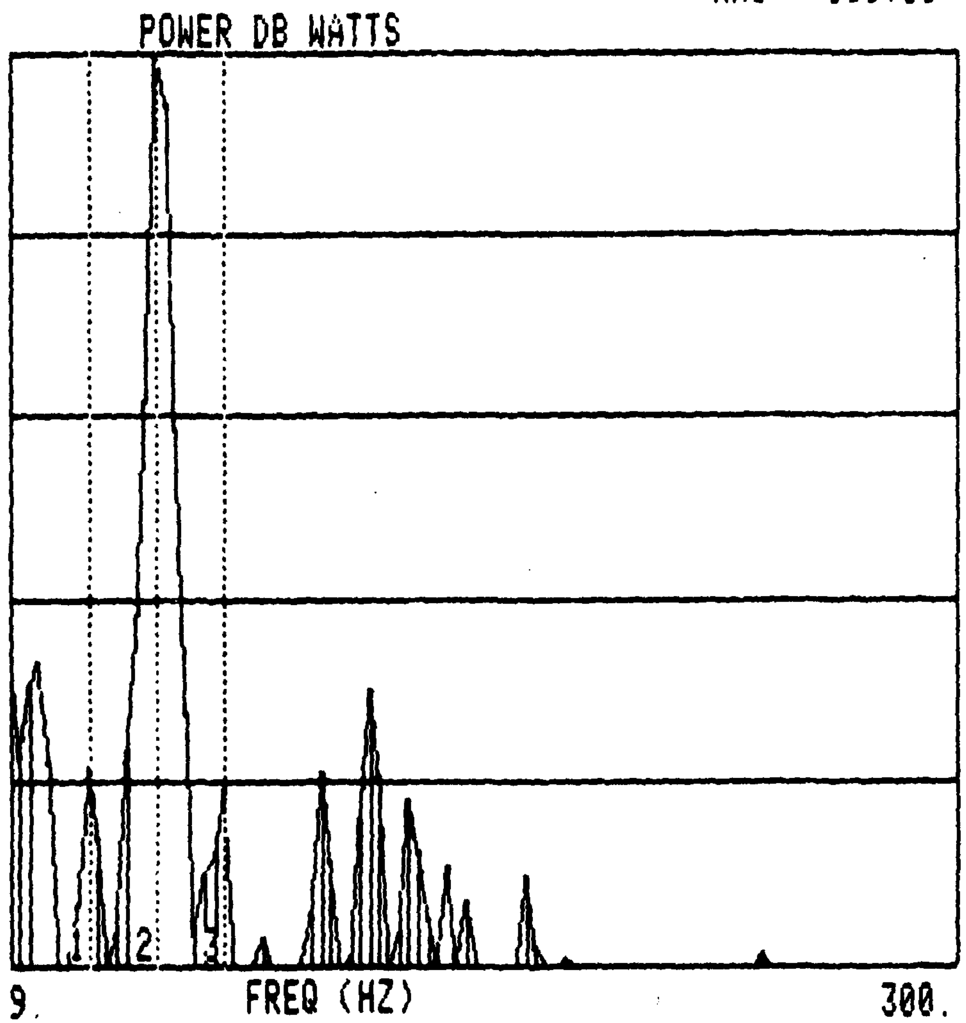

TEST1
P#16
FREQ= 9.000
MAG= 110.63
0.1240E+03
INTENSITY
POWER DB WATTS
NET OVERALL
NEGATIVES
POSITIVES
DONE
1 F & M
39.000 99.92
2
54.000 123.69
3
69.000 107.90
0.9400E+02
1
2
3
9.
FREQ (HZ)
300.

TEST1

P#18

FREQ= 9.000
MAG= 105.08

0.1250E+03
INTENSITY



0.9500E+02

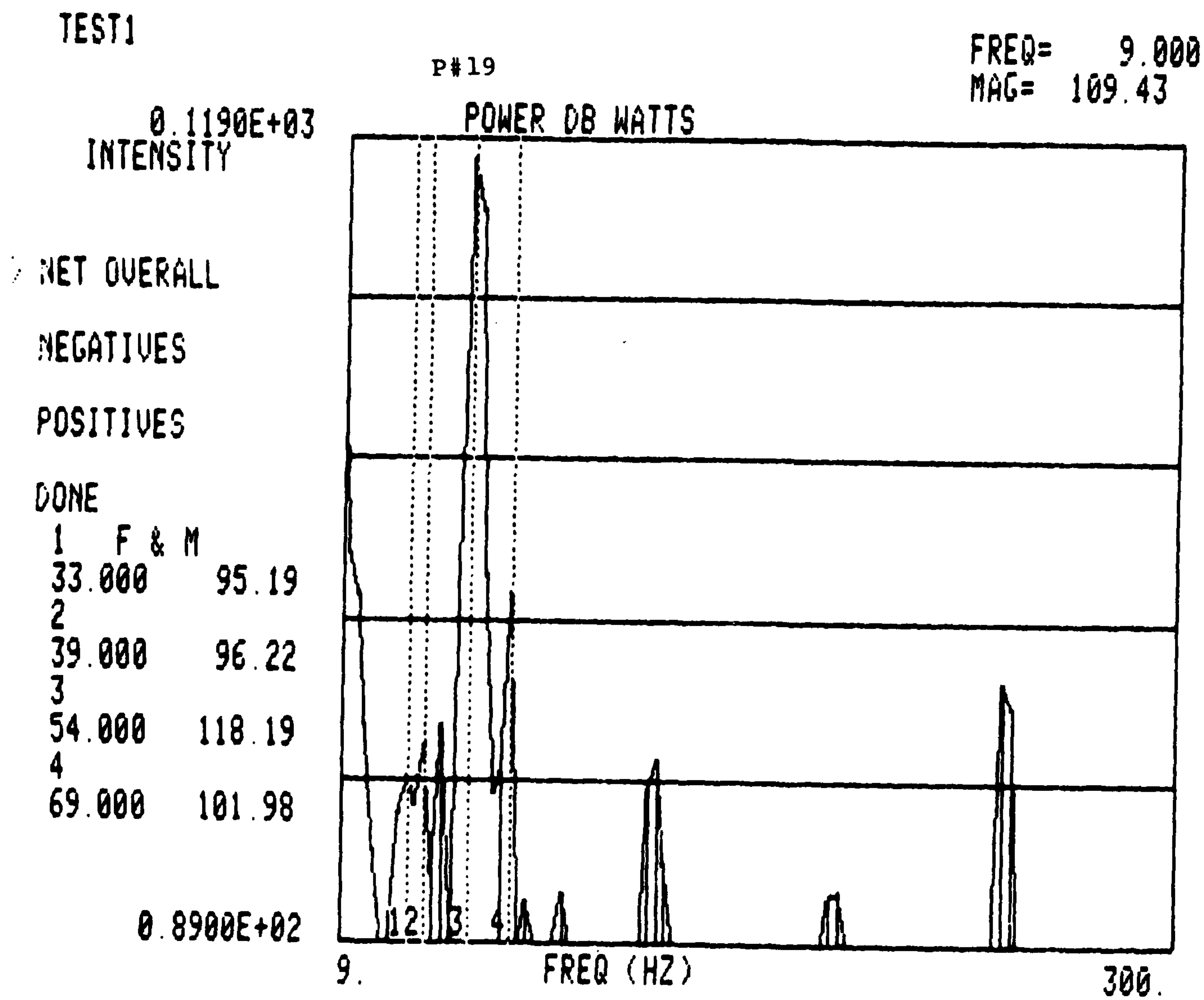
> NET OVERALL

NEGATIVES

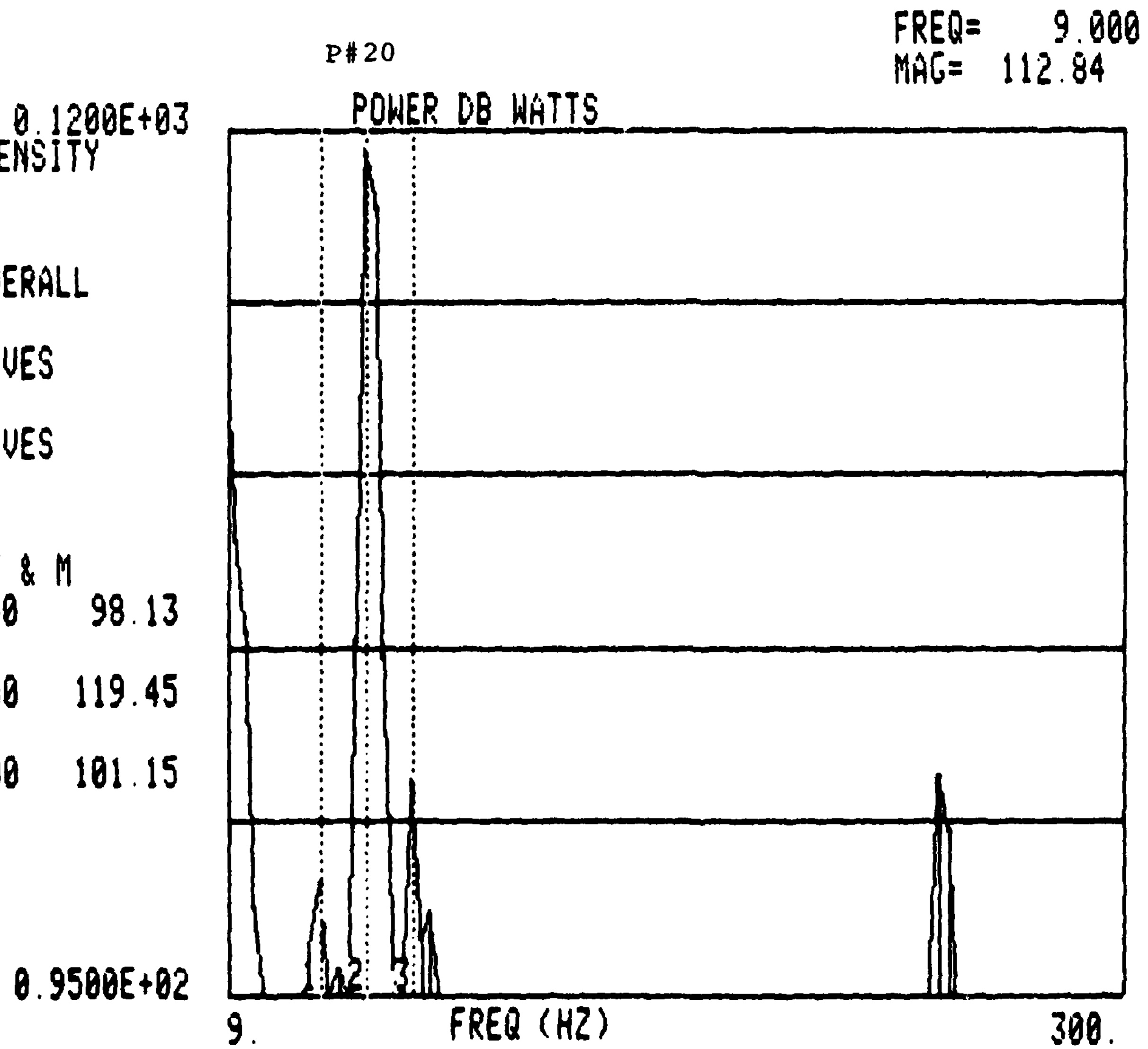
POSITIVES

DONE

1 F & M
33.000 101.42
2
54.000 124.85
3
75.000 100.57


TEST1
P#19
FREQ= 9.000
MAG= 109.43
0.1190E+03
INTENSITY
POWER DB WATTS
NET OVERALL
NEGATIVES
POSITIVES
DONE
1 F & M
33.000 95.19
2
39.000 96.22
3
54.000 118.19
4
69.000 101.98
0.8900E+02
1 2 3 4
9.
FREQ (HZ)
300.

TEST1



INTENSITY

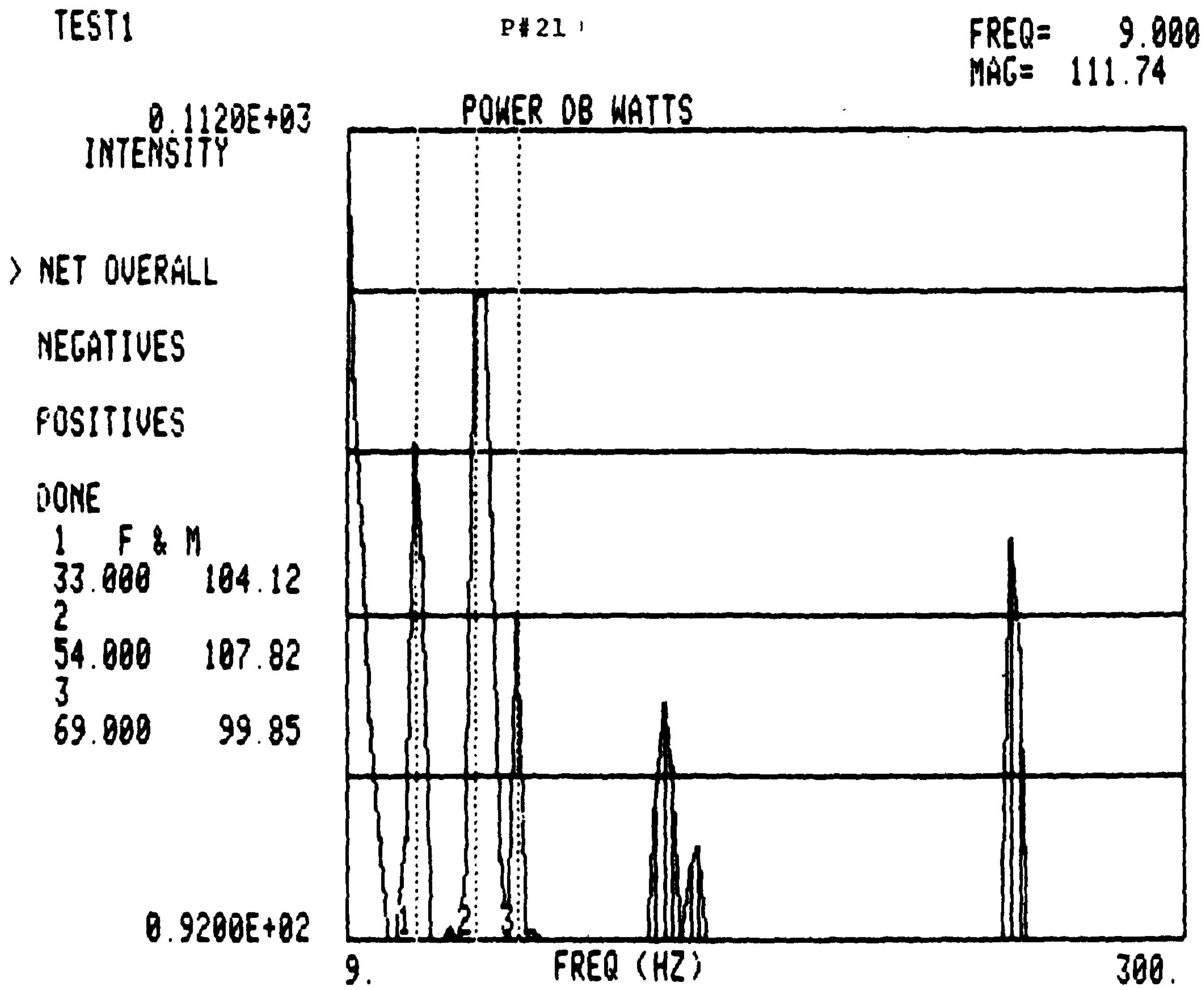
NET OVERALL

NEGATIVES

POSITIVES

DONE

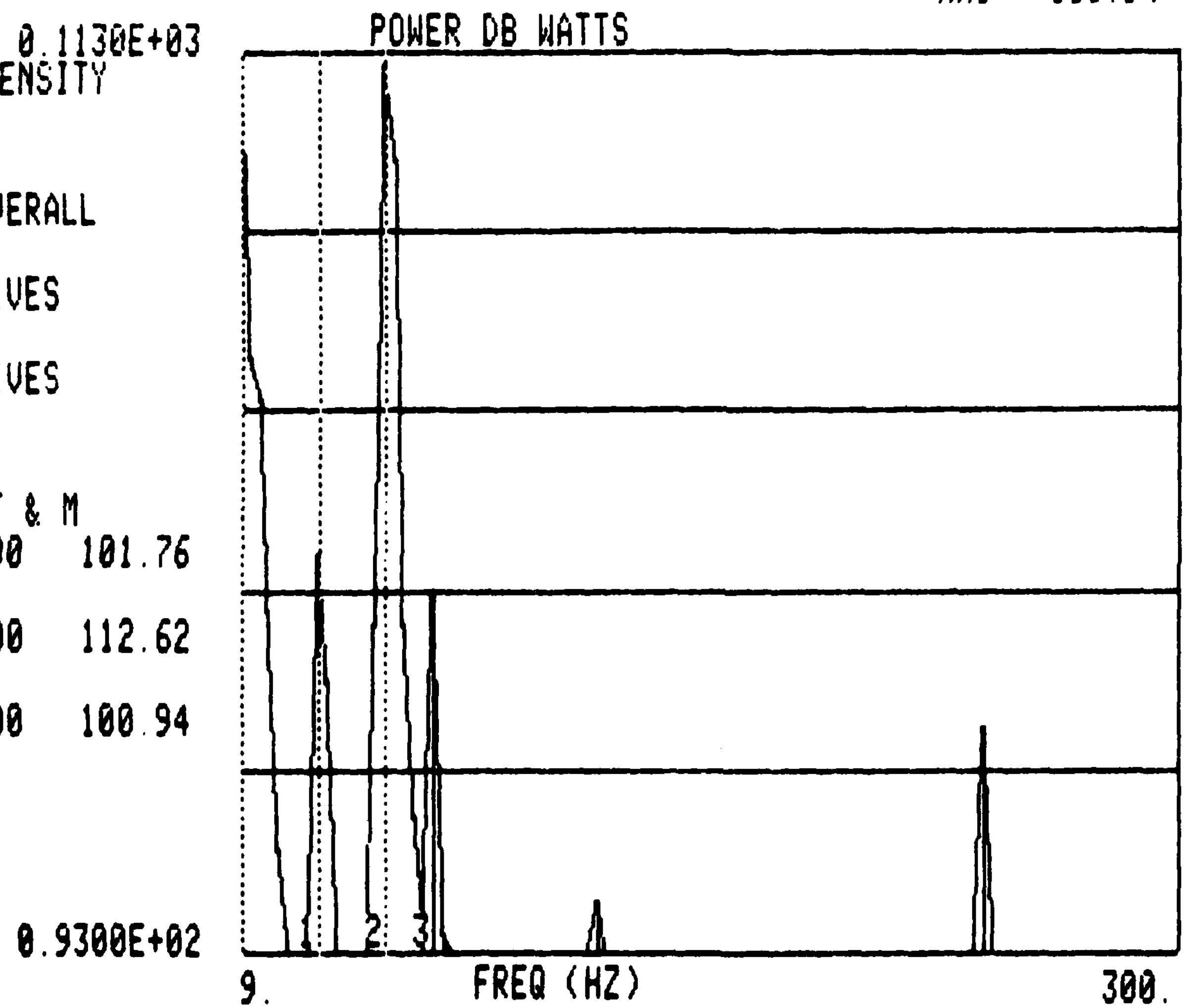
1   F & M
39.000   98.13
2
54.000   119.45
3
69.000   101.15


TEST1
P#21
FREQ= 9.000
MAG= 111.74
0.1120E+03
INTENSITY
POWER DB WATTS
> NET OVERALL
NEGATIVES
POSITIVES
DONE
1 F & M
33.000 104.12
2
54.000 107.82
3
69.000 99.85
0.9200E+02
9.
FREQ (HZ)
300.
1
2
3

TEST1

FREQ= 69.000
MAG= 100.94

P#22



> NET OVERALL

NEGATIVES

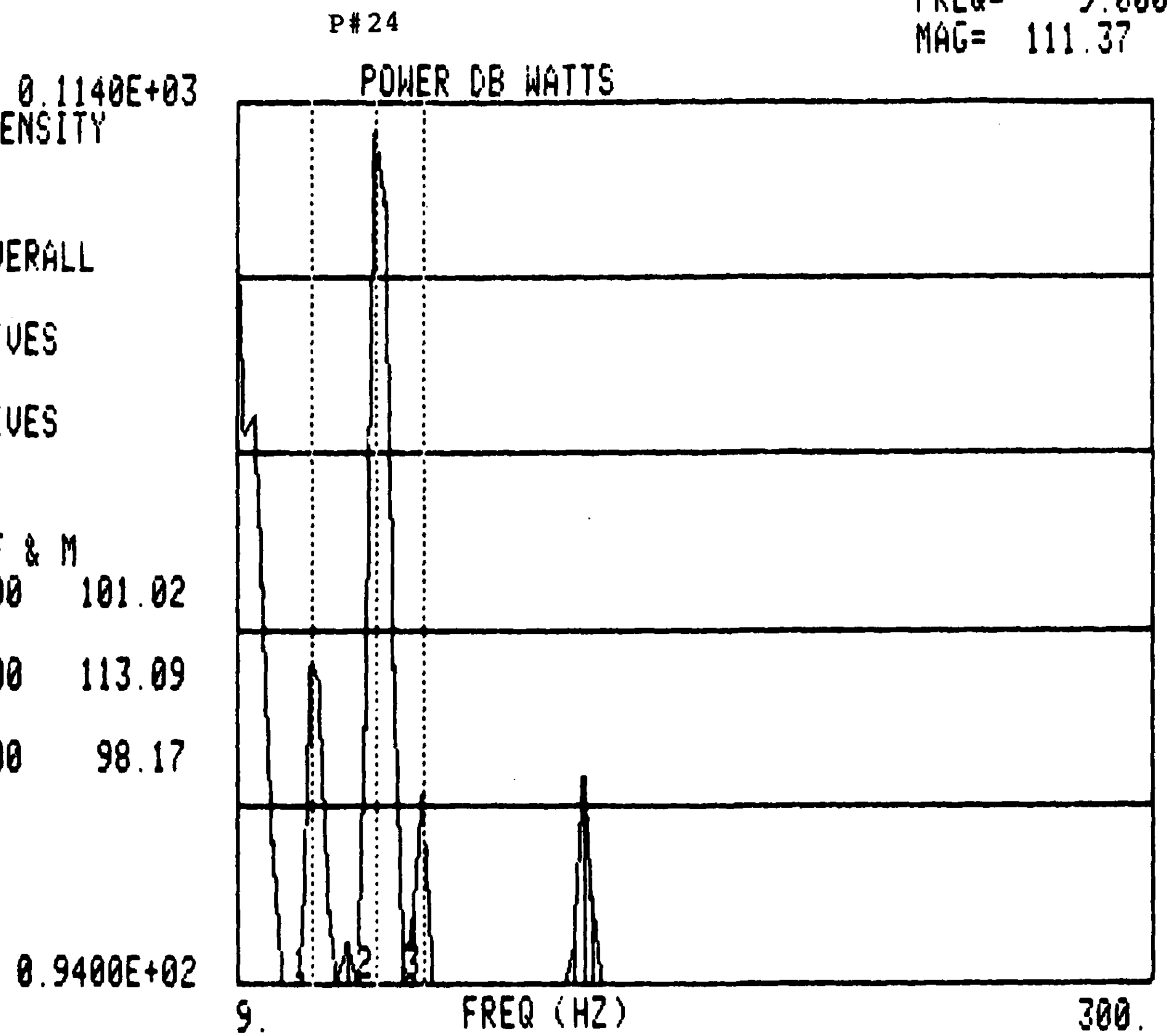
POSITIVES

DONE

1 F & M
33.000 101.76
2
54.000 112.62
3
69.000 100.94

TEST1

FREQ= 9.000
MAG= 111.37



> NET OVERALL

NEGATIVES

POSITIVES

DONE

1	F & M	
	33.000	101.02
2		
	54.000	113.09
3		
	69.000	98.17

APPENDIX B

DATA POINTS FOR SECOND FLIGHT

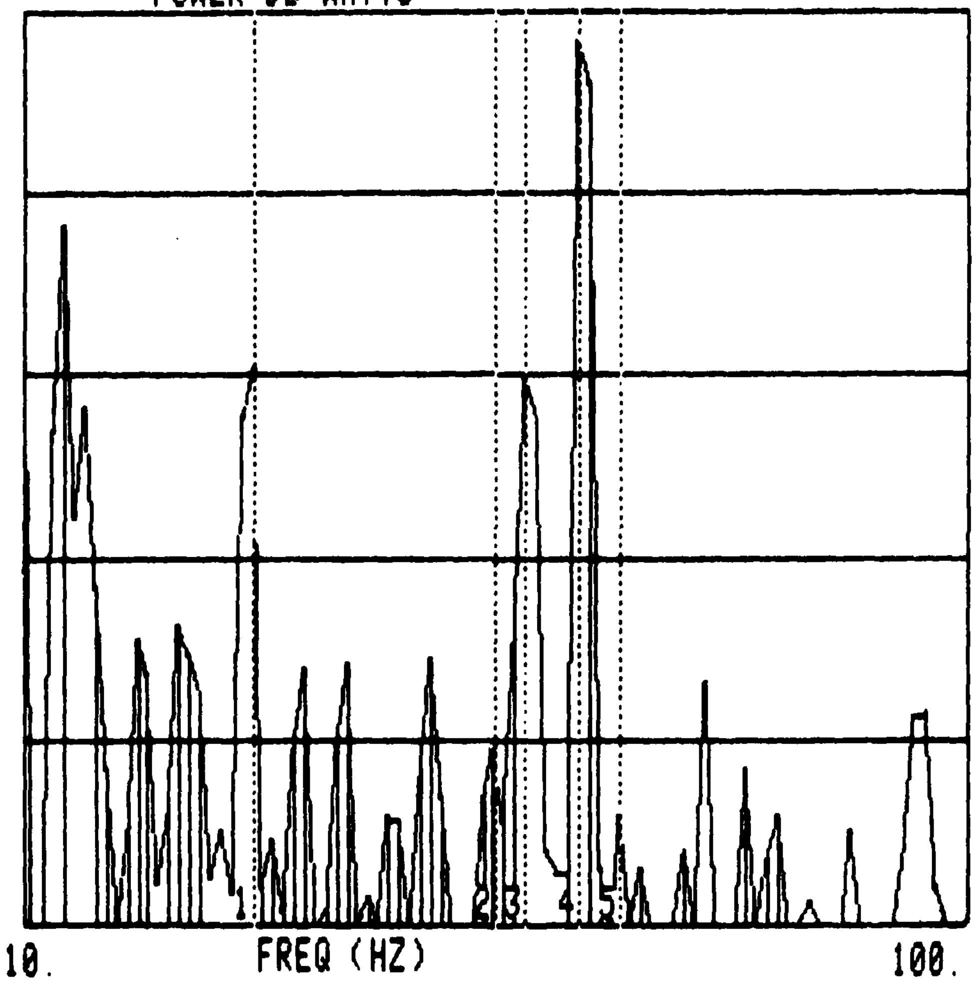
TEST2

P#4 RUMBLE 3

FREQ= 10.000
MAG= 93.60

POWER DB WATTS

0.1000E+03
INTENSITY



> NET OVERALL

NEGATIVES

POSITIVES

DONE

1	F & M
32.000	90.05
2	
55.000	79.73
3	
58.000	89.84
4	
63.000	99.14
5	
67.000	78.06

0.7500E+02

TEST2

P#4 NO RUMBLE

FREQ= 10.000
MAG= 95.33

POWER DB WATTS

0.9600E+02
INTENSITY

> NET OVERALL

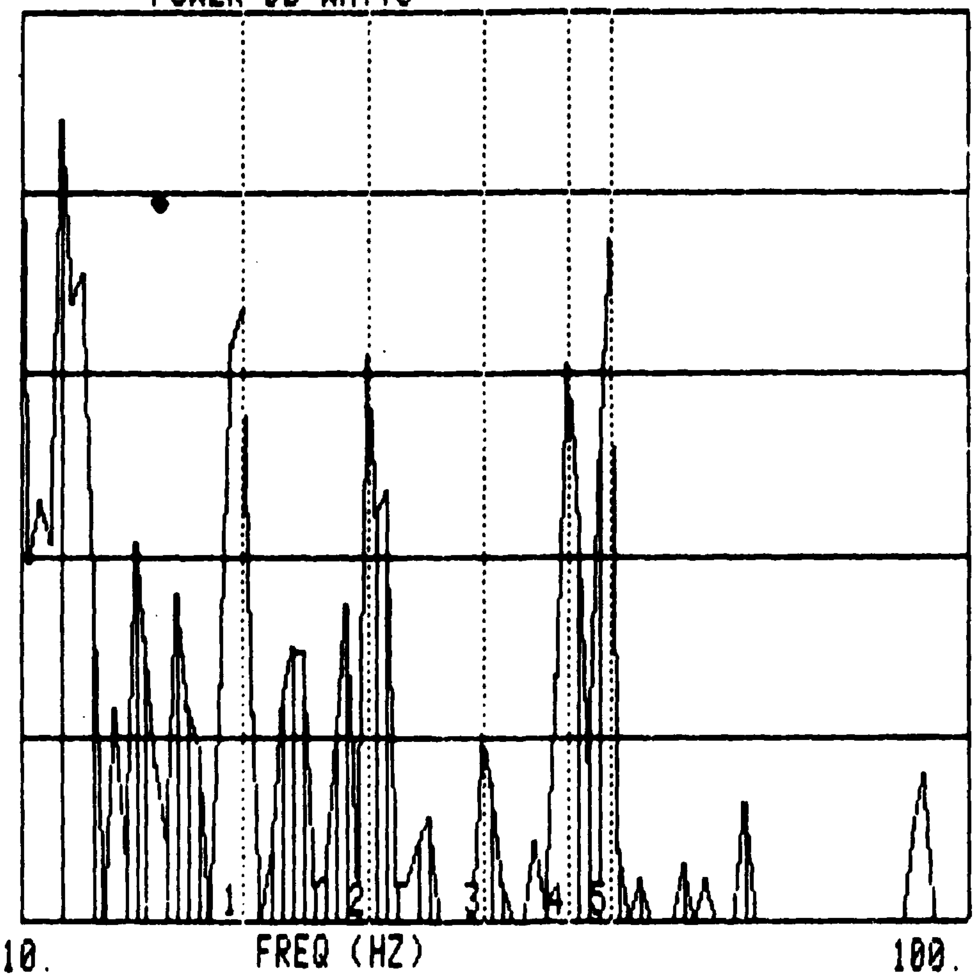
NEGATIVES

POSITIVES

DONE

1 F & M	
31.000	89.38
2	
43.000	88.48
3	
54.000	80.14
4	
62.000	88.19
5	
66.000	90.89

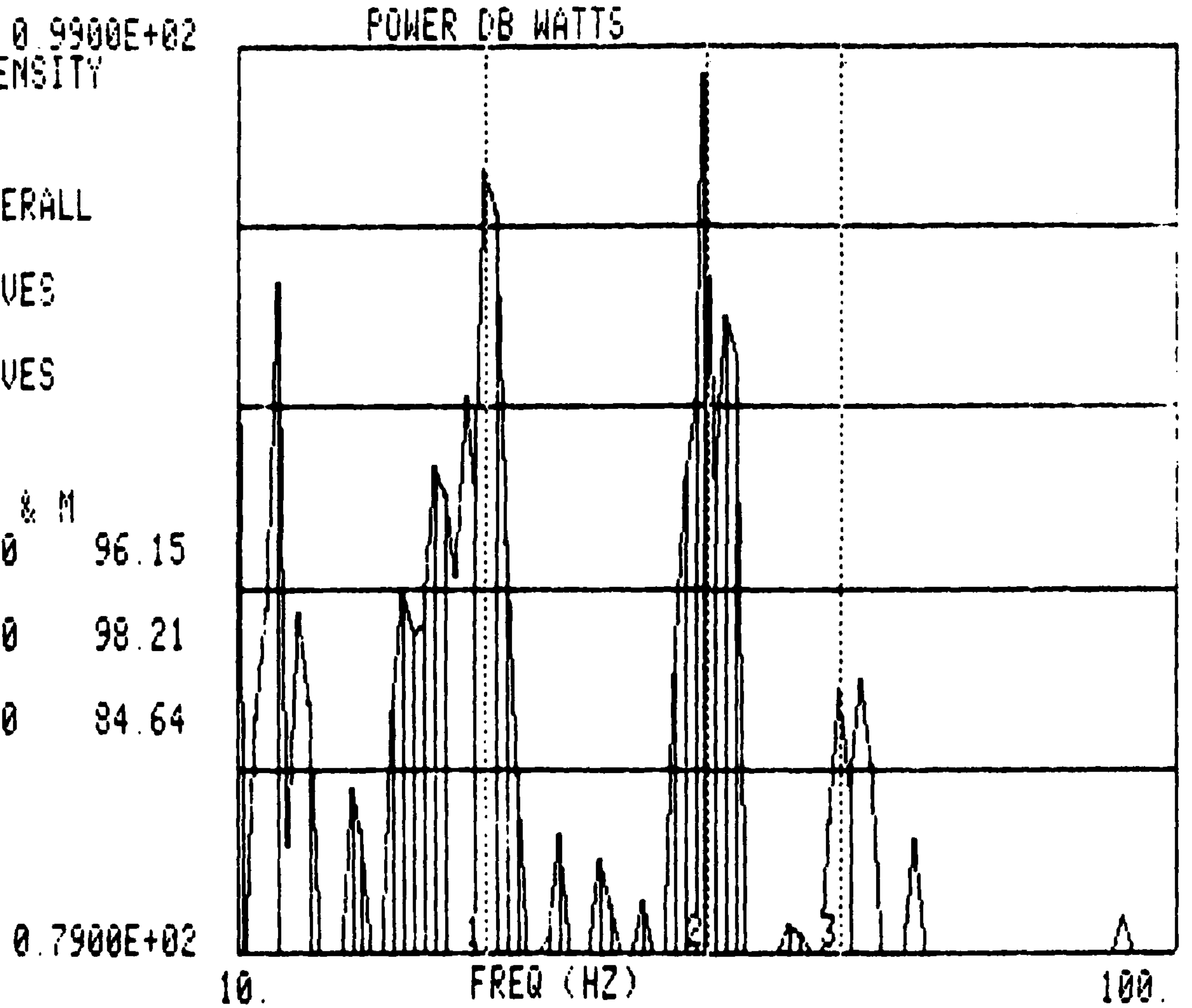
0.7600E+02



TEST2

FREQ= 10.000
MAG= 96.68

P#4 RUMBLE #2 & #3



> NET OVERALL

NEGATIVES

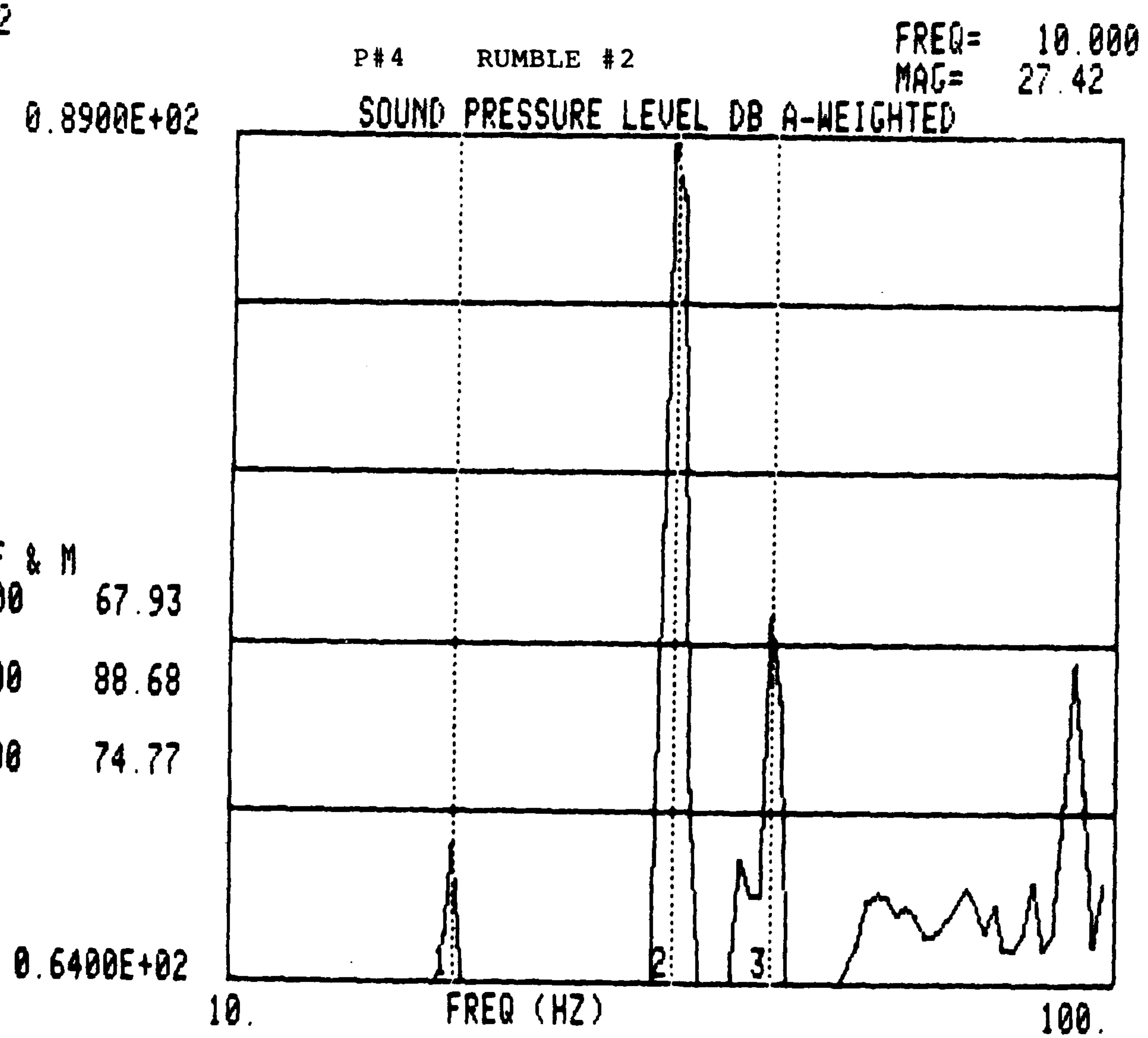
POSITIVES

ZONE

1	F & M	
	34.000	96.15
2		
	55.000	98.21
3		
	68.000	84.64

TEST2

P#4 RUMBLE #2



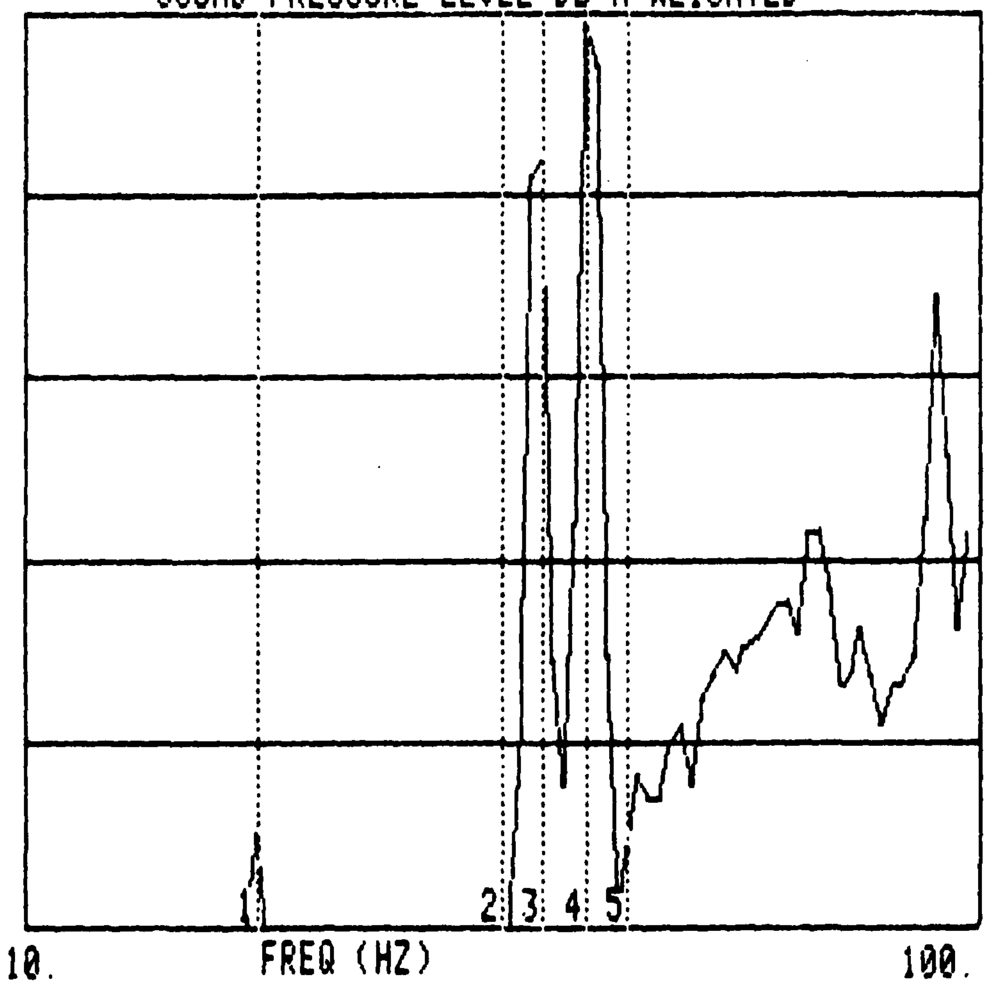
1	F & M
33.000	67.93
2	
55.000	88.68
3	
65.000	74.77

TEST2

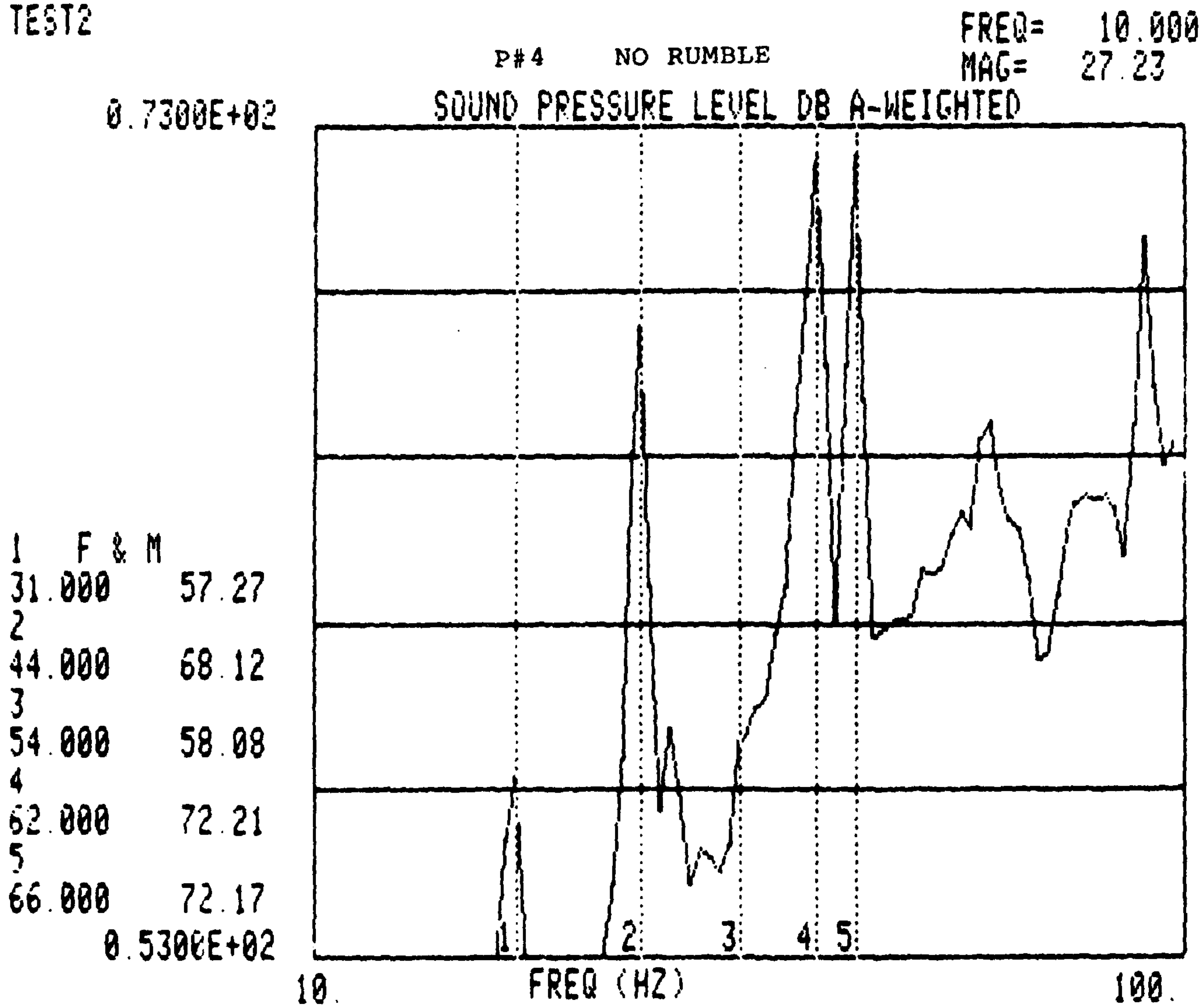
P#4 RUMBLE #3

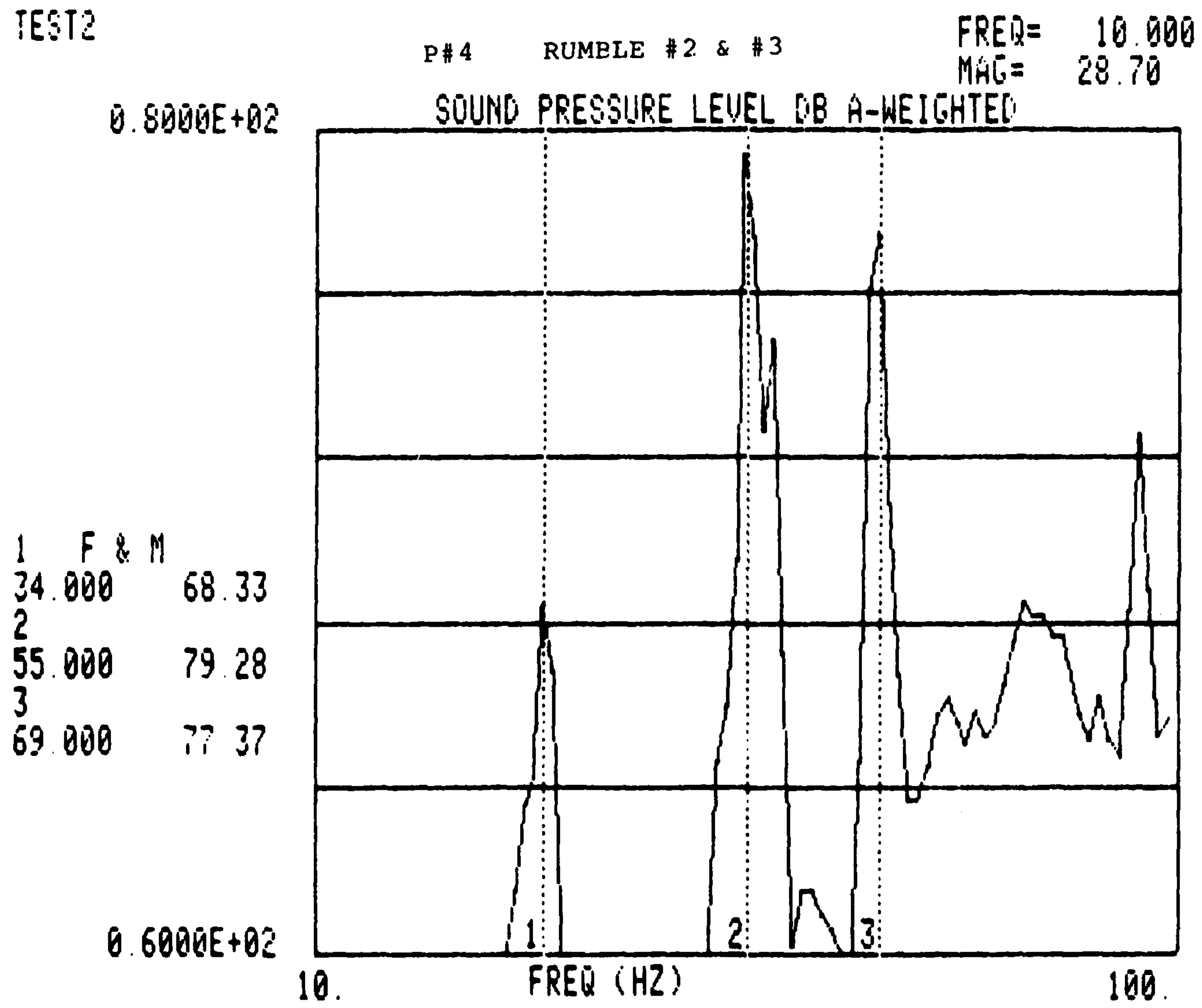
FREQ= 10.000
MAG= 24.37

SOUND PRESSURE LEVEL DB A-WEIGHTED

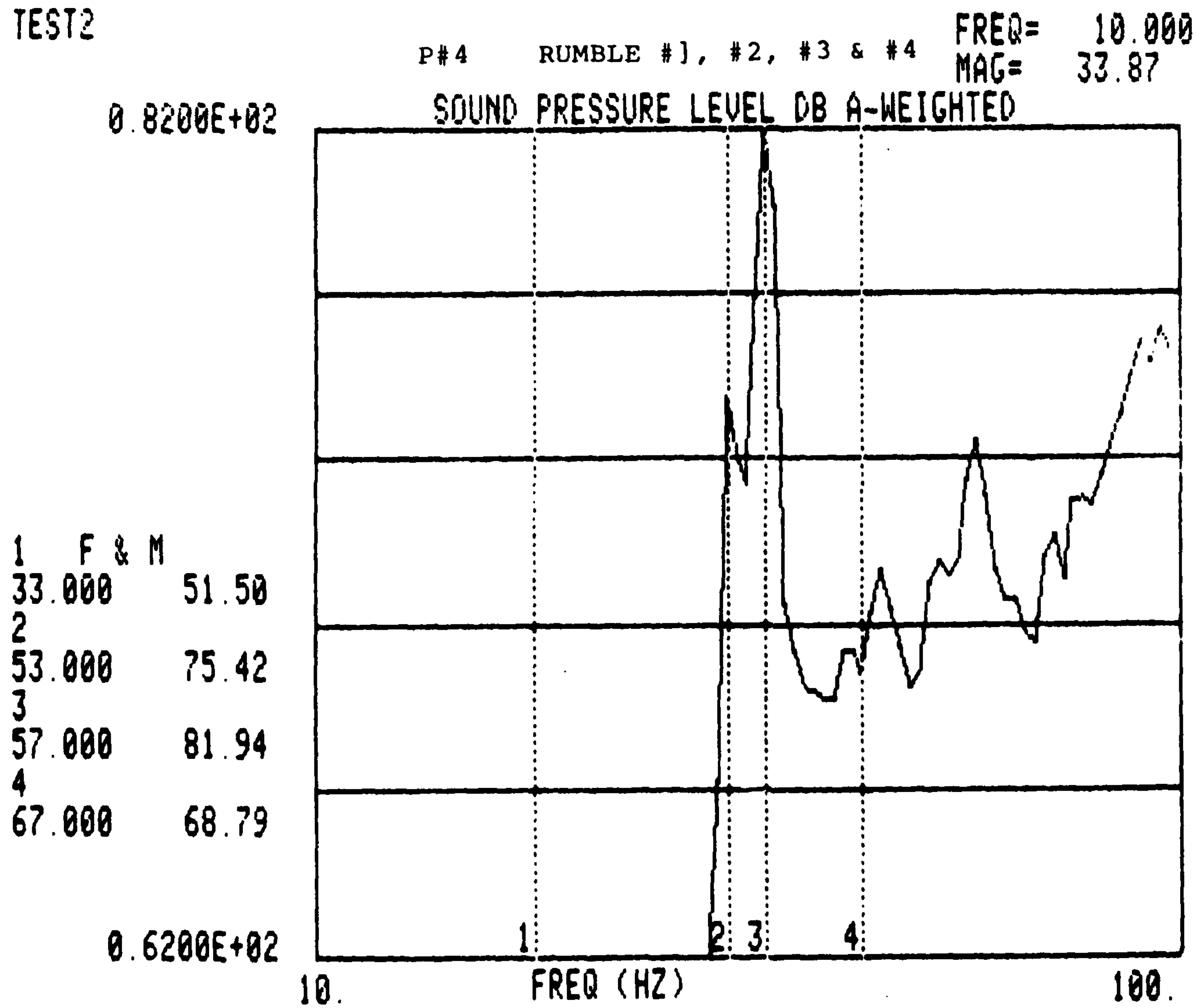


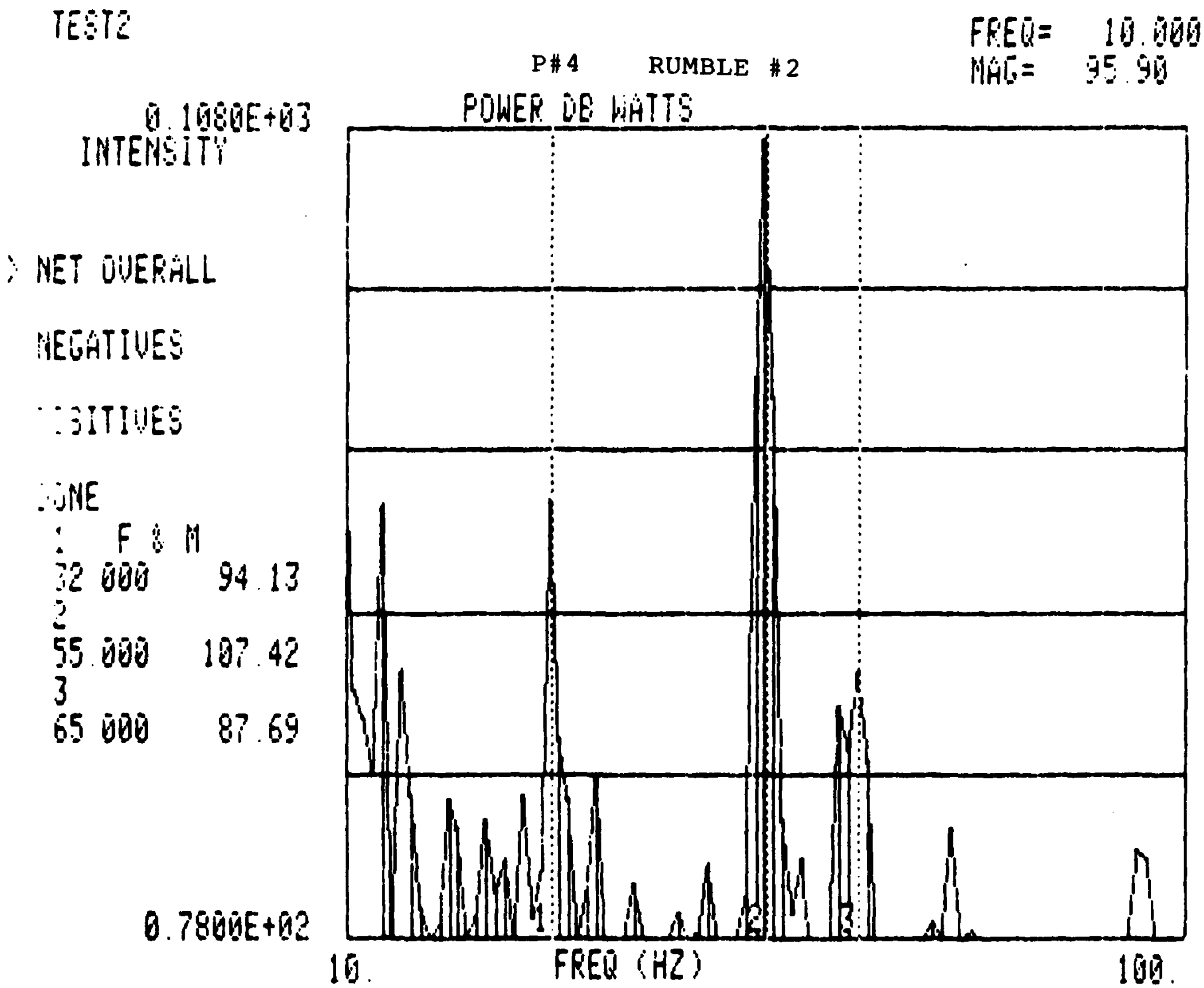
	F & M	
1	32.000	61.96
2	55.000	58.47
3	59.000	76.74
4	63.000	79.66
5	67.000	61.72


TEST2
FREQ= 10.000
MAG= 27.23
P#4 NO RUMBLE
SOUND PRESSURE LEVEL DB A-WEIGHTED
0.7300E+02
1 F & M
31.000 57.27
2
44.000 68.12
3
54.000 58.08
4
62.000 72.21
5
66.000 72.17
0.5300E+02
1
2
3
4
5
10.
FREQ (HZ)
100.



TEST2
P#4 RUMBLE #2 & #3
FREQ= 10.000
MAG= 28.70
SOUND PRESSURE LEVEL DB A-WEIGHTED
0.8000E+02
0.6000E+02
1 F & M
34.000 68.33
2
55.000 79.28
3
69.000 77.37
1
2
3
10.
FREQ (HZ)
100.


TEST2
P#4 RUMBLE #1, #2, #3 & #4
FREQ= 10.000
MAG= 33.87
SOUND PRESSURE LEVEL DB A-WEIGHTED
0.8200E+02
0.6200E+02
1
2
3
4
10.
FREQ (HZ)
100.
1 F & M
33.000 51.50
2
53.000 75.42
3
57.000 81.94
4
67.000 68.79


TEST2
P#4 RUMBLE #2
FREQ= 10.000
MAG= 95.90
POWER DB WATTS
0.1080E+03
INTENSITY
> NET OVERALL
NEGATIVES
ITIVES
ONE
F & M
32.000 94.13
2
55.000 107.42
3
65.000 87.69
0.7800E+02
1
2
3
10.
FREQ (HZ)
100.

TEST2

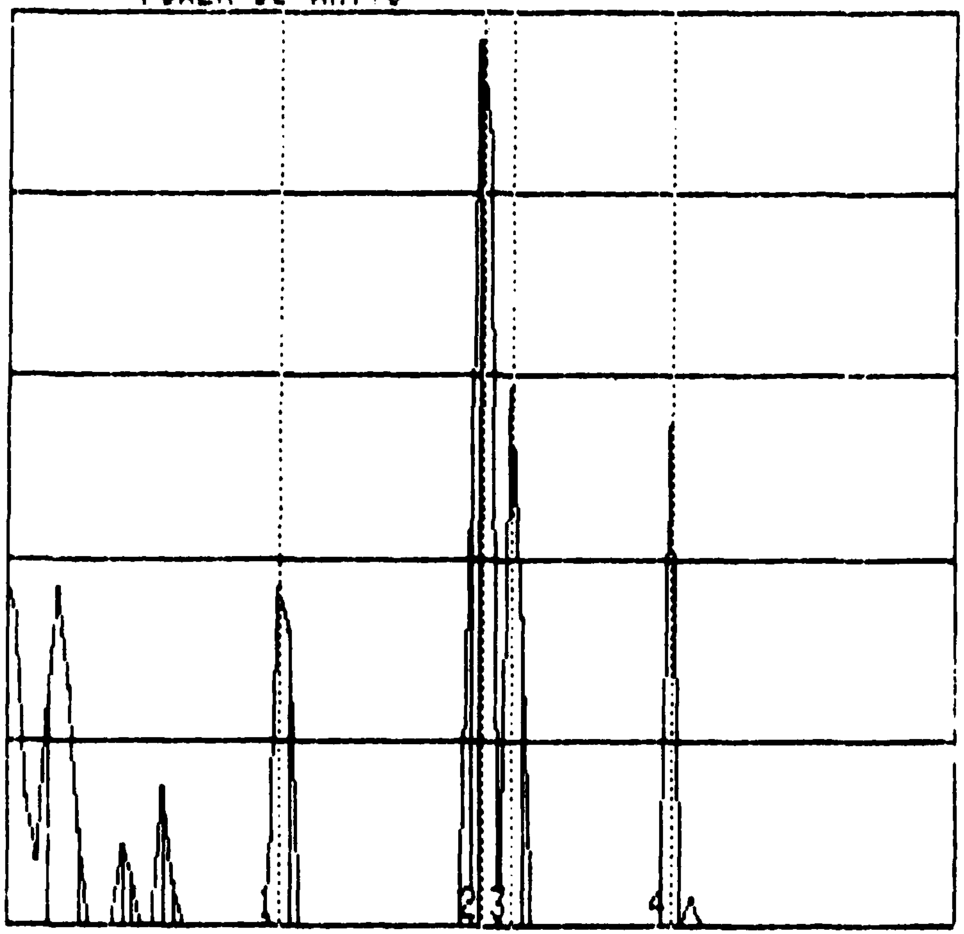
P#4 RUMBLE #2 & #3

RIGHT TURN].5G's

FREQ= 10.000
MAG= 90.38

0.1030E+03
INTENSITY

POWER DB WATTS



10. FREQ (HZ) 100.

0.8300E+02

> NET OVERALL

NEGATIVES

POSITIVES

ZONE

ZONE	F & M	
1	36.000	90.29
2	55.000	102.27
3	58.000	94.73
4	73.000	93.82

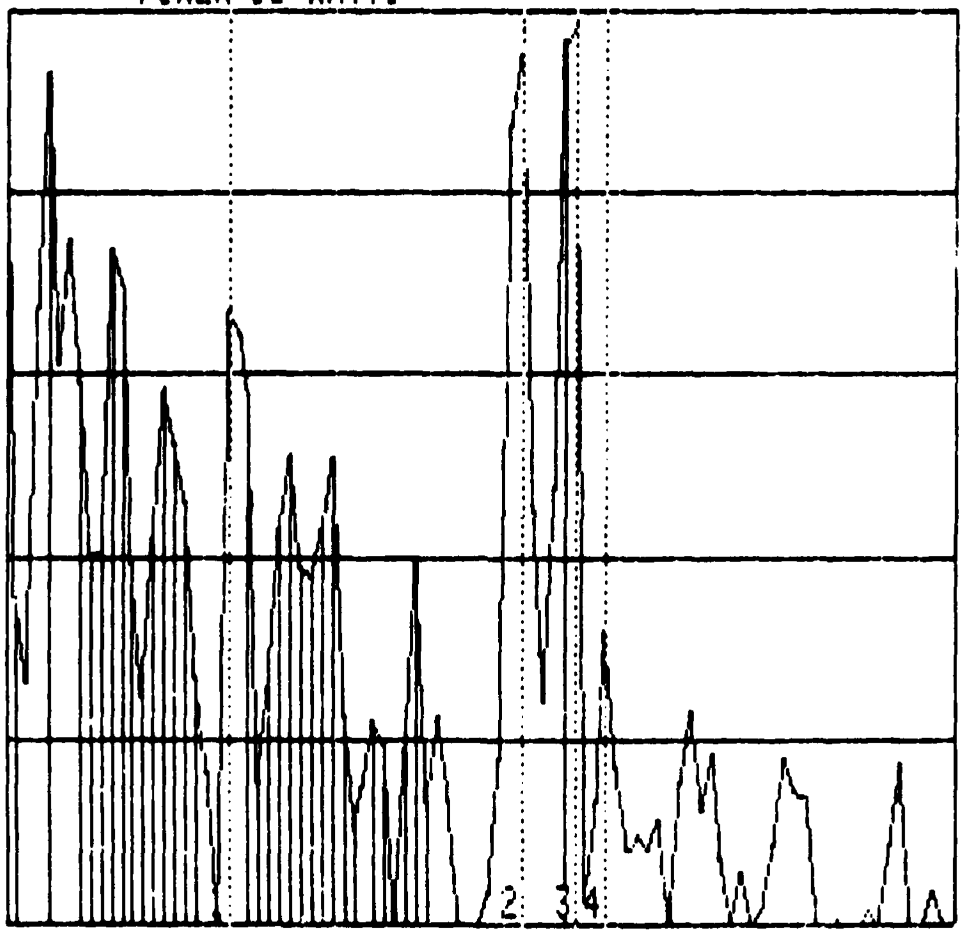
TEST2

FREQ= 10.000
MAG= 94.68

P#12 RUMBLE #3

POWER DB WATTS

0.9700E+02
INTENSITY



0.7200E+02

10. FREQ (HZ) 100.

> NET OVERALL

NEGATIVES

POSITIVES

DONE

1	F & M	
	31.000	88.68
2		
	59.000	95.79
3		
	64.000	96.50
4		
	67.000	79.98

TEST2

P#4 RUMBLE #1, #2, #3 & #4

FREQ= 10.000
MAG= 99.11

0.1020E+03
INTENSITY

> NET OVERALL

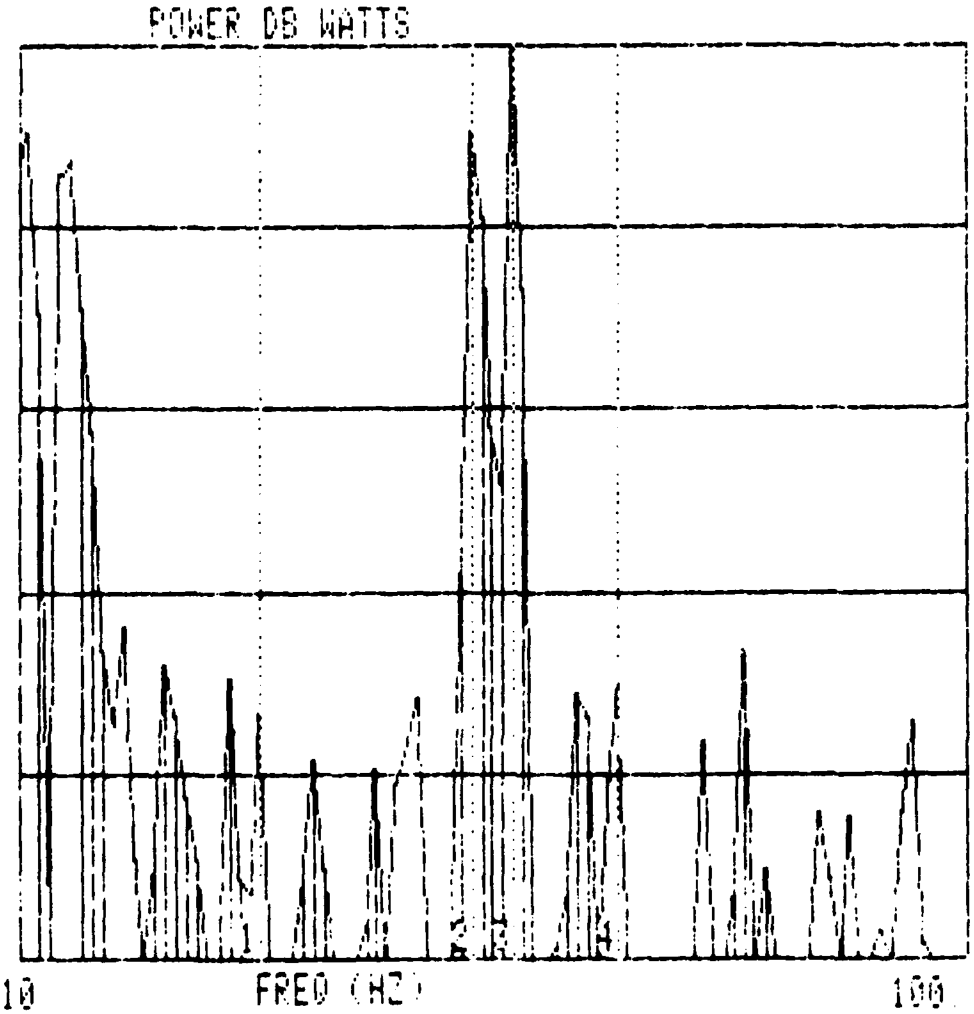
NEGATIVES

POSITIVES

DONE

1 F & M
33.000 87.33
2
53.000 99.98
3
7.000 101.88
4
67.000 87.79

0.8200E+02



TEST2

P#]7 RUMBLE #[, #2, #3 & #4

FREQ= 10.000
MAG= 96.94

POWER DB WATTS

0.1090E+03
INTENSITY

> NET OVERALL

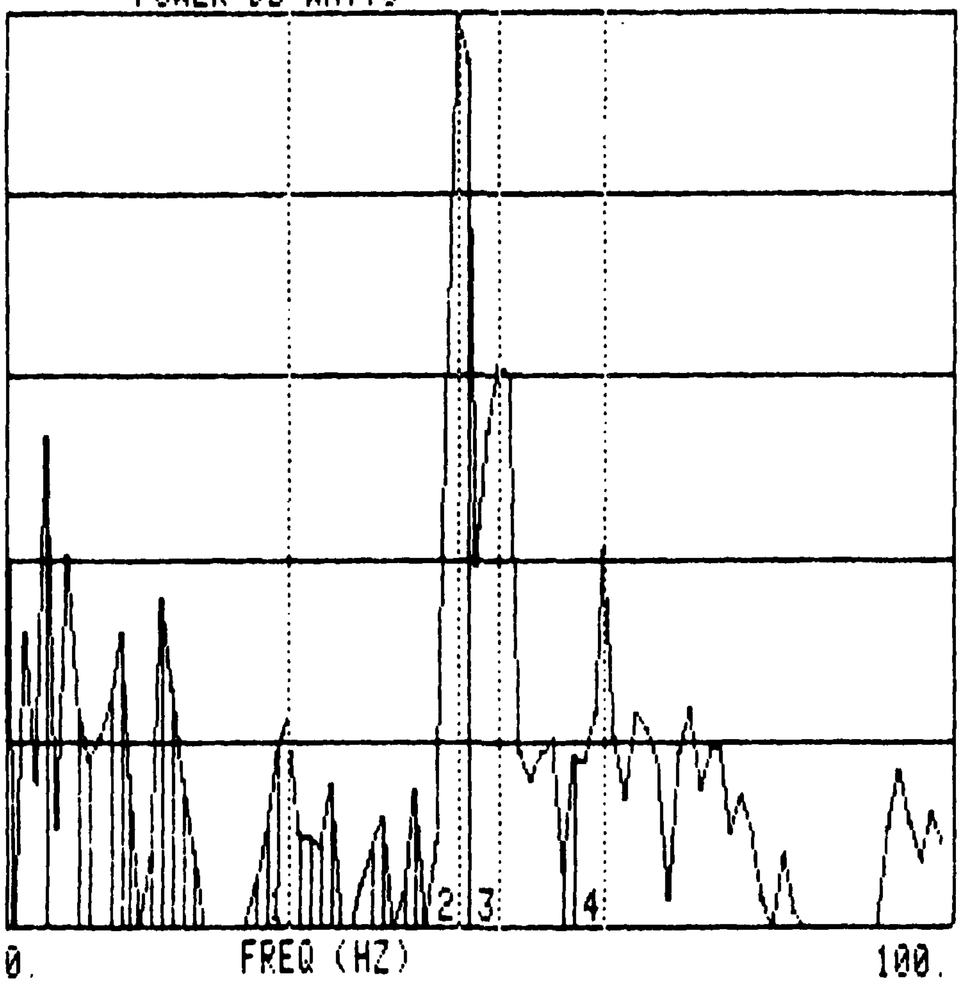
NEGATIVES

POSITIVES

ZONE

	F & M	
1	37.000	85.76
2	53.000	108.82
3	57.000	97.33
4	67.000	91 27

0.7900E+02



TEST2

0.9800E+02
INTENSITY

> NET OVERALL

NEGATIVES

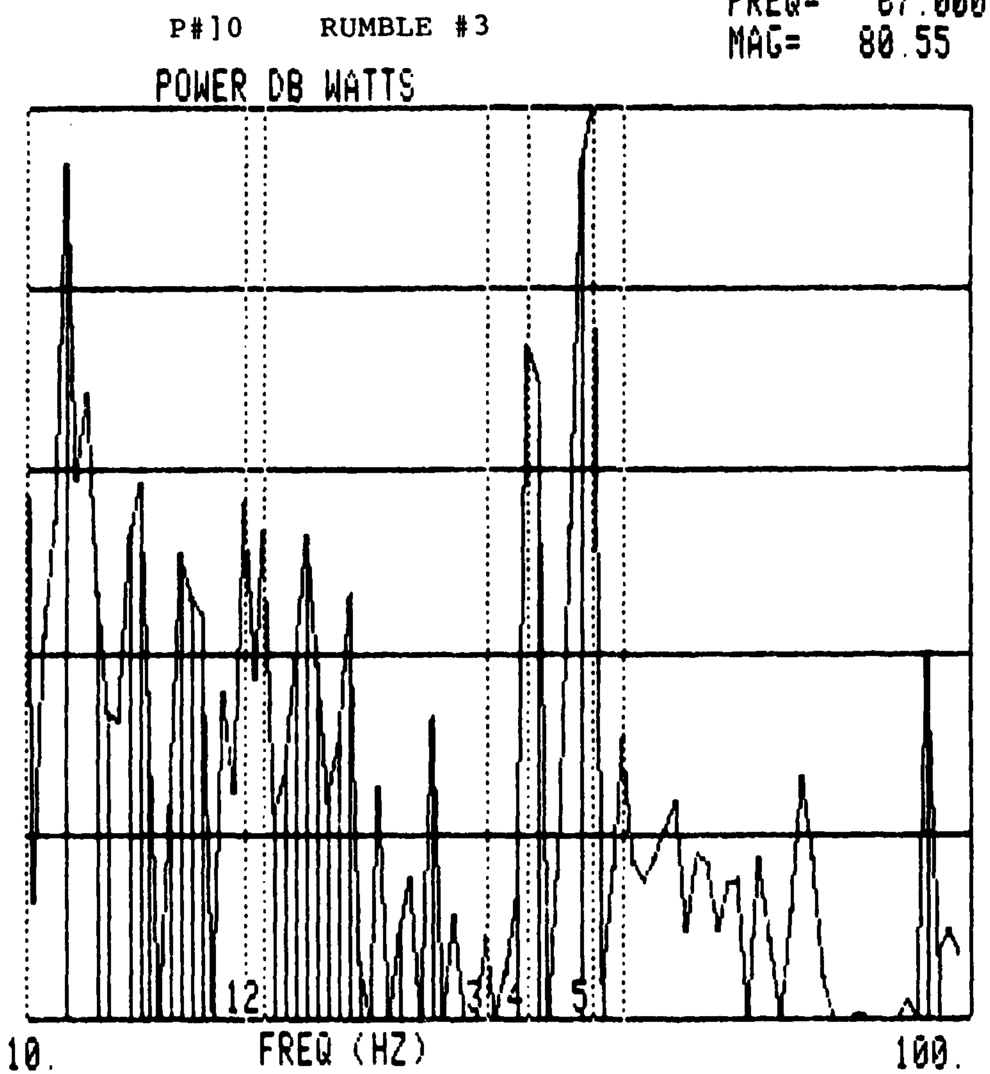
POSITIVES

DONE

1 F & M
31.000 87.07
2
33.000 86.52
3
54.000 75.23
4
58.000 91.45
5
64.000 97.97

0.7300E+02

FREQ= 67.000
MAG= 80.55



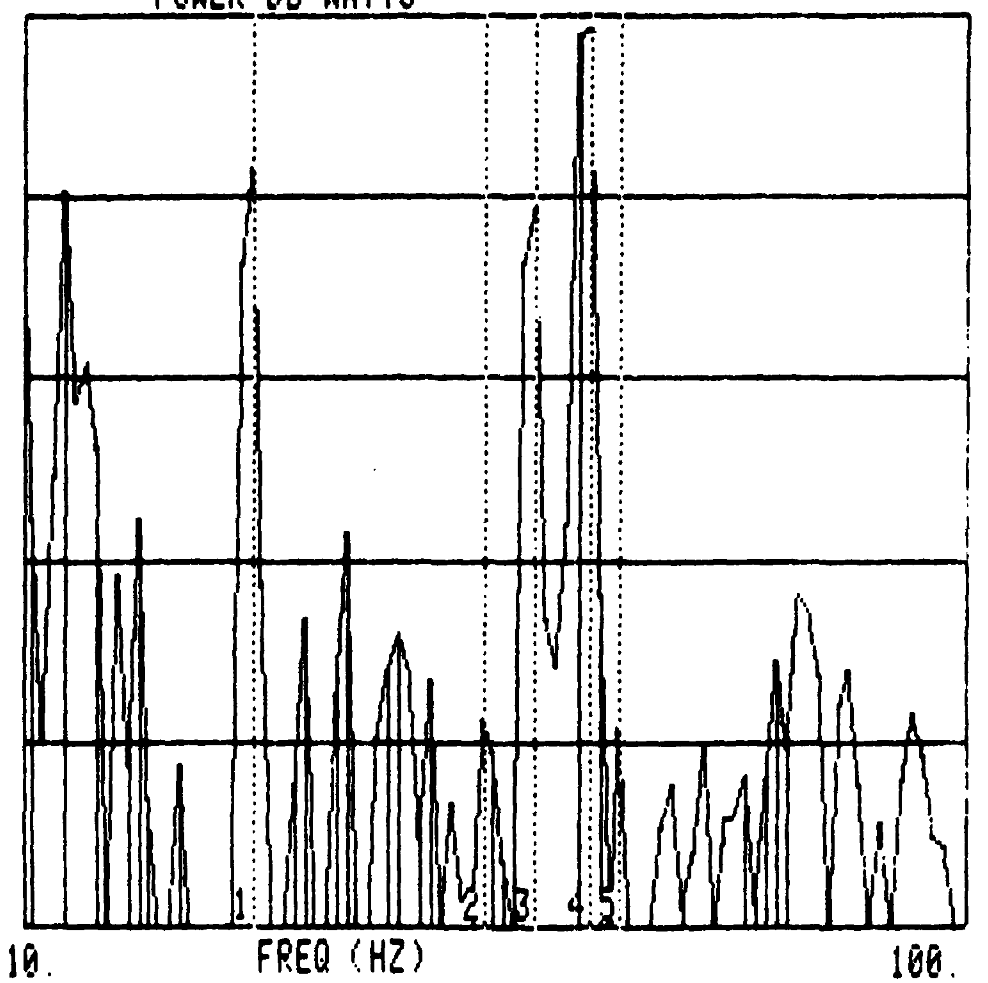
TEST2

P#6 RUMBLE #3

FREQ= 10.000
MAG= 92.07

POWER DB WATTS

0.9800E+02
INTENSITY



> NET OVERALL

NEGATIVES

POSITIVES

DONE

1	F & M
32.000	93.72
2	
54.000	78.71
3	
59.000	92.54
4	
64.000	97.68
5	
67.000	78.41

0.7300E+02

TEST2

P#5 RUMBLE #3

FREQ= 10.000
MAG= 94.63

0.1010E+03
INTENSITY

> NET OVERALL

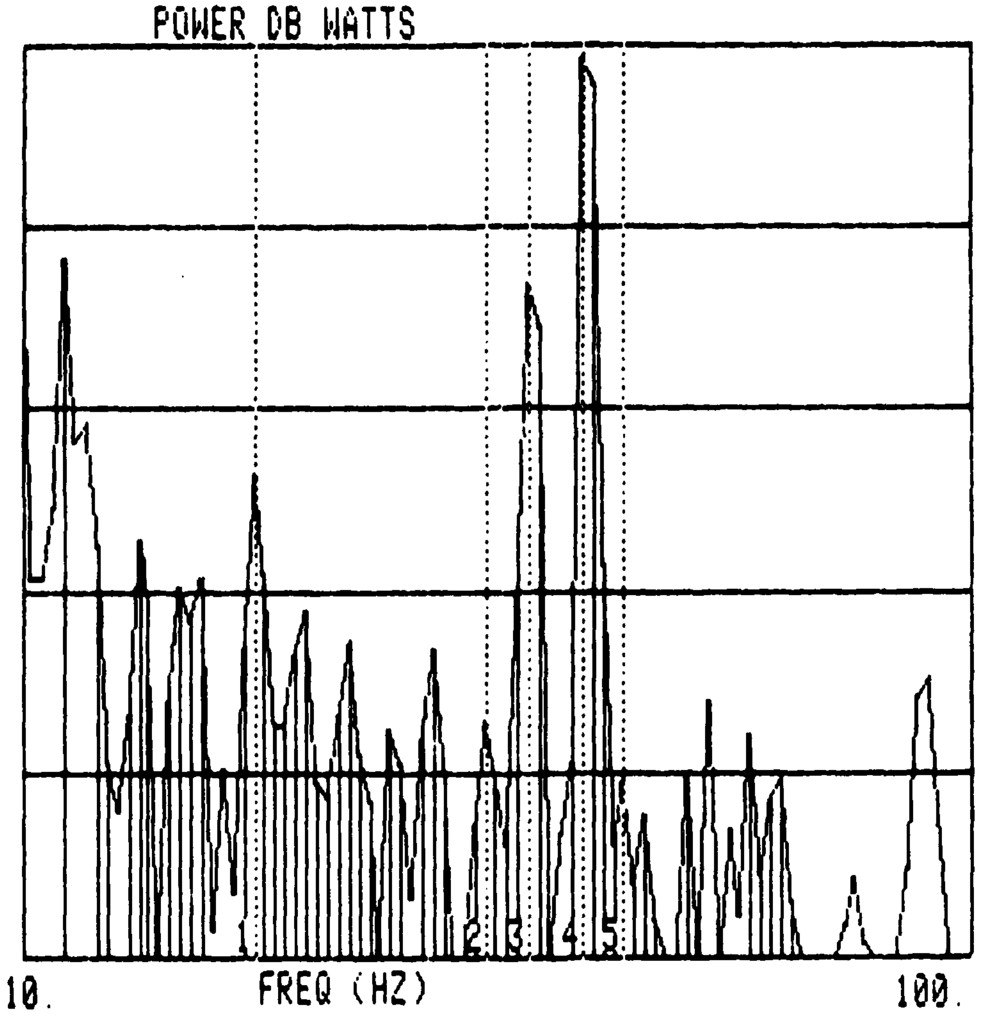
NEGATIVES

POSITIVES

ZONE

	F & M	
1		
	32.000	86.65
2		
	54.000	78.57
3		
	58.000	92.95
4		
	63.000	100.25
5		
	67.000	76.52

0.7100E+02



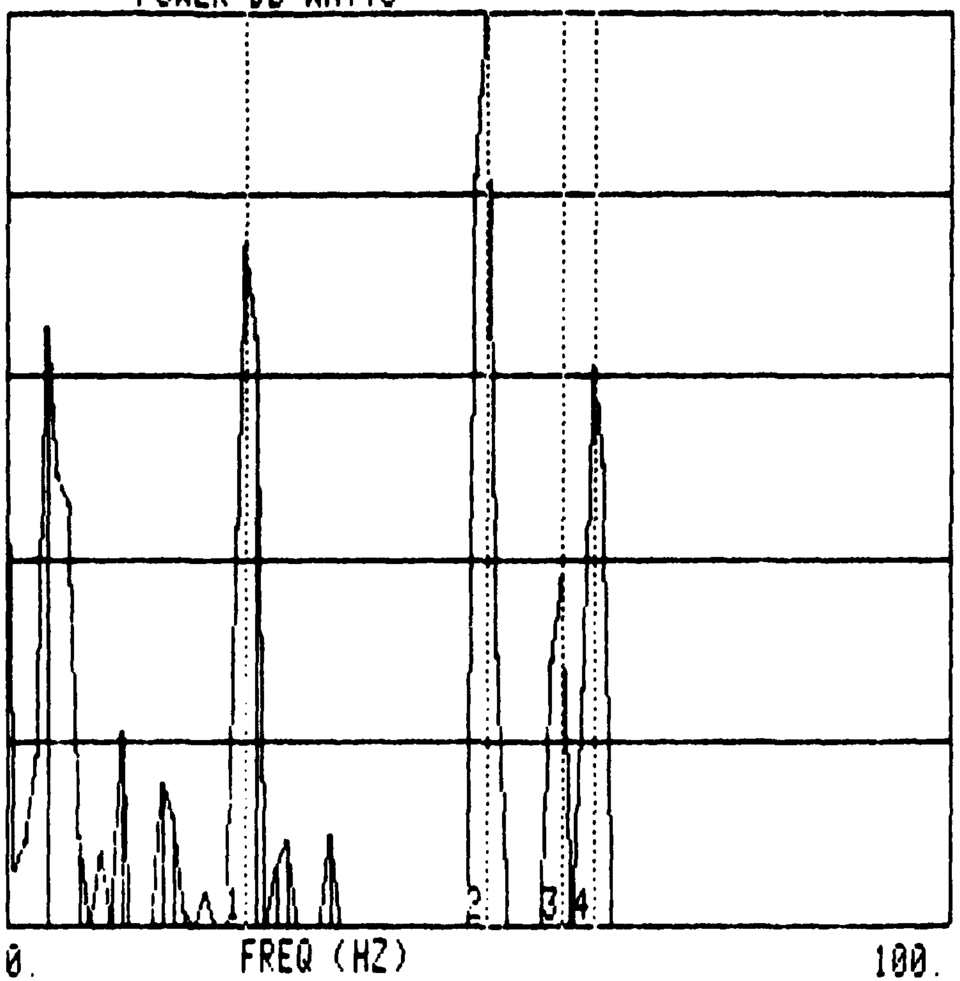
TEST2

P#]7 RUMBLE #2

FREQ= 10.000
MAG= 94.89

POWER DB WATTS

0.1030E+03
INTENSITY



0.8300E+02

〉 NET OVERALL

NEGATIVES

POSITIVES

DONE

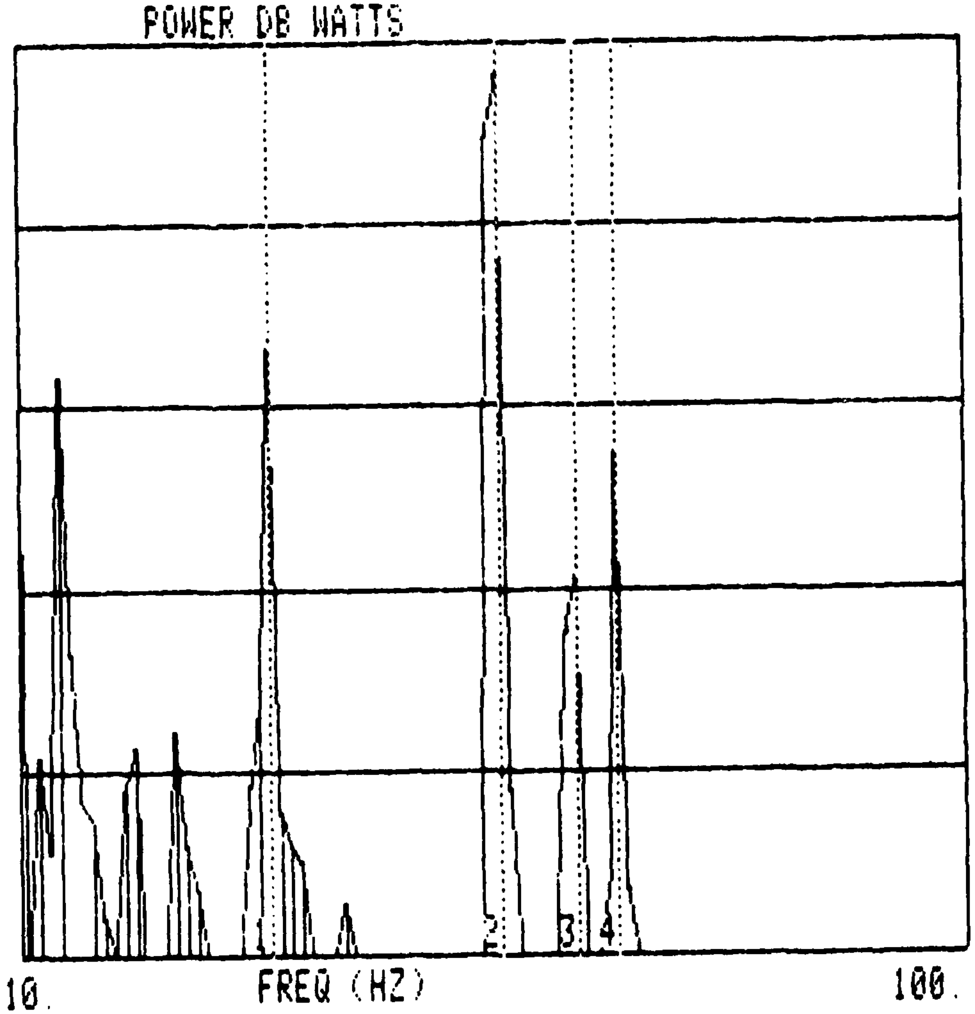
1	F & M
33.000	97.84
2	
56.000	102.80
3	
63 000	90 51
4	
66.000	95.24

TEST2

P#]2 RUMBLE #2

FREQ= 10.000
MAG= 95.32

0.1020E+03
INTENSITY



0.8200E+02

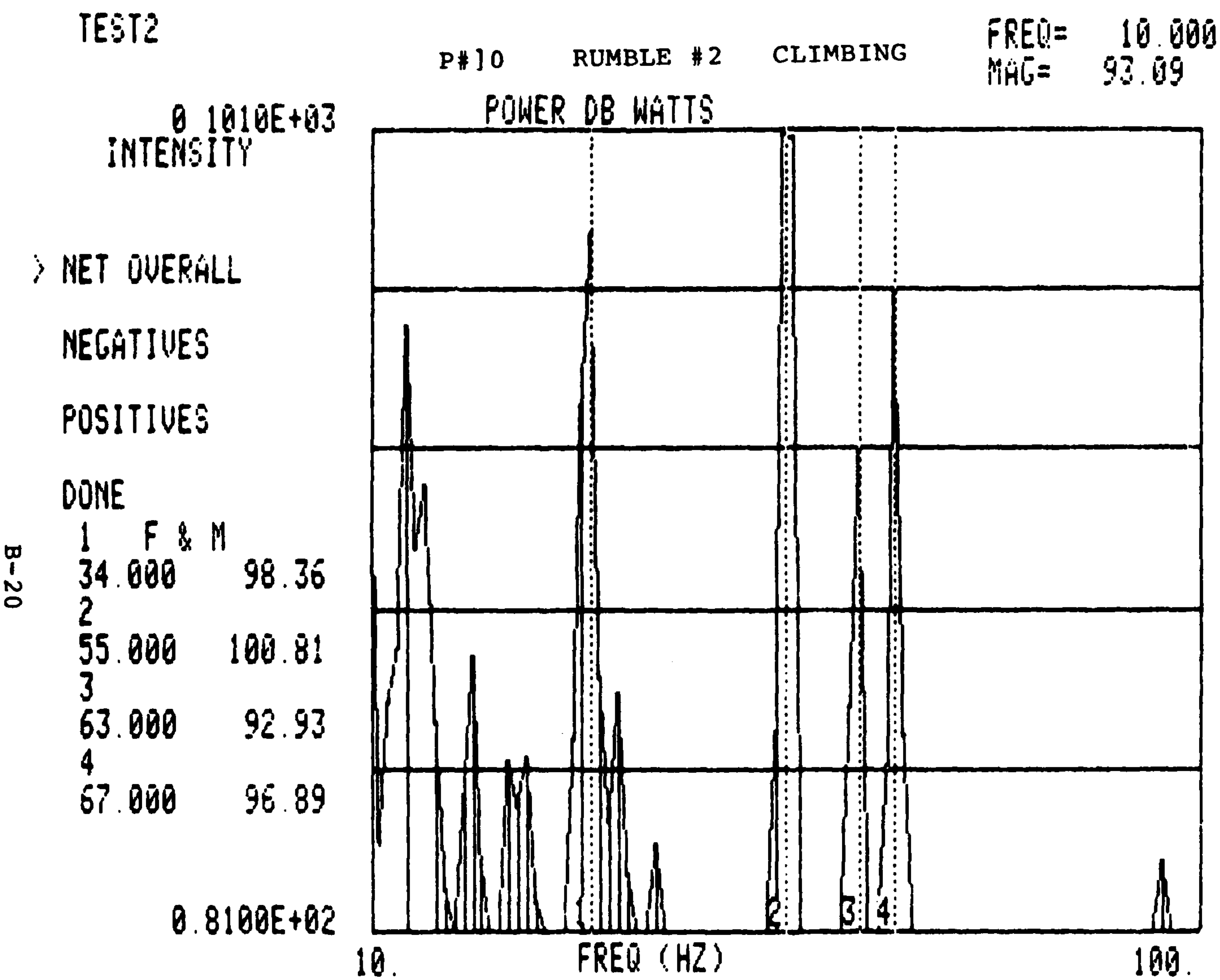
> NET OVERALL

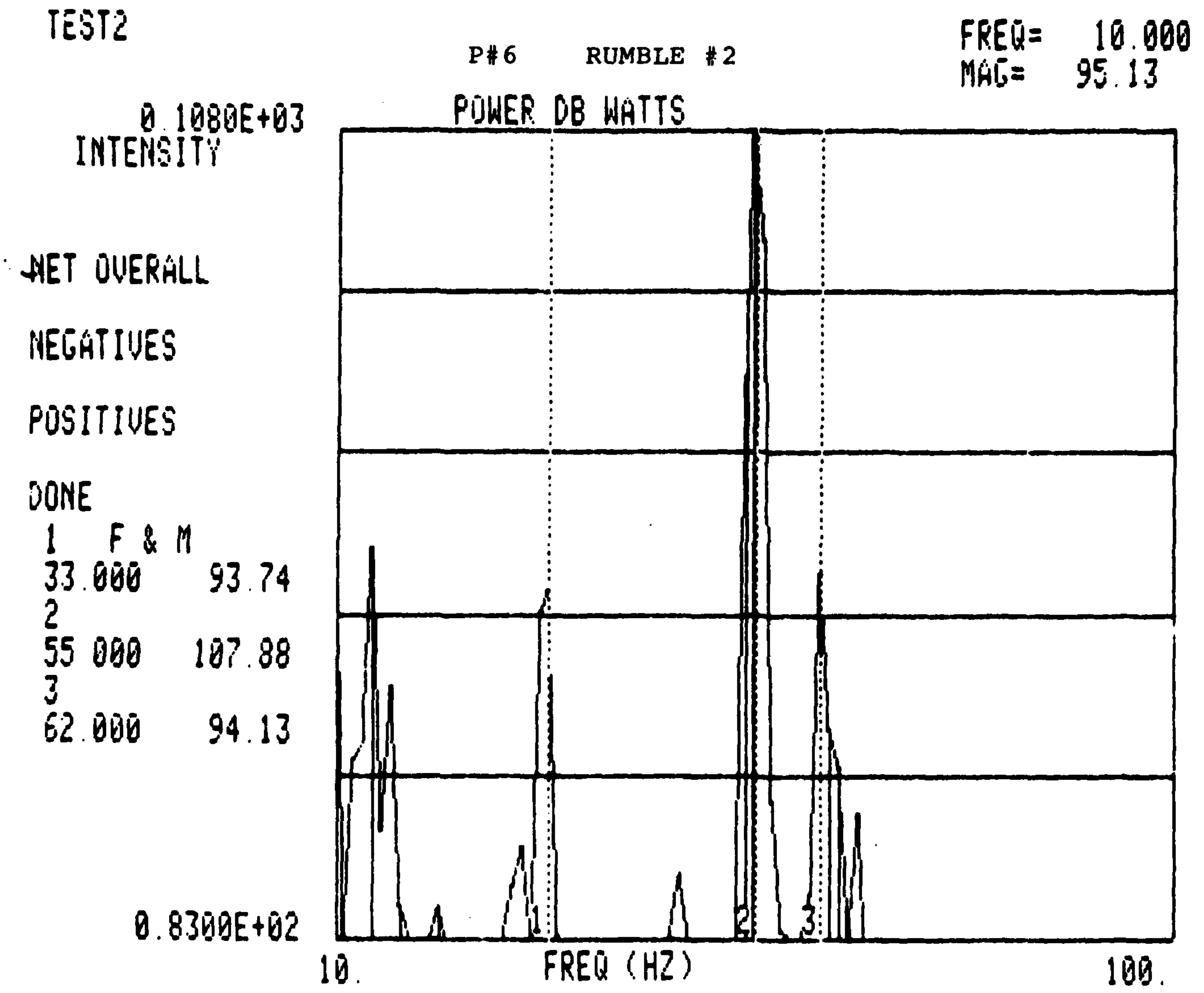
NEGATIVES

POSITIVES

ZONE

1	F & M	
	34.000	95.23
2		
	56.000	101.15
3		
	63.000	90.23
4		
	67.000	92.91


TEST2
P#10 RUMBLE #2 CLIMBING
FREQ= 10.000
MAG= 93.09
POWER DB WATTS
0.1010E+03
INTENSITY
> NET OVERALL
NEGATIVES
POSITIVES
DONE
1 F & M
34.000 98.36
2
55.000 100.81
3
63.000 92.93
4
67.000 96.89
0.8100E+02
2
3
4
10.
FREQ (HZ)
100.


TEST2
P#6 RUMBLE #2
FREQ= 10.000
MAG= 95.13
POWER DB WATTS
0.1080E+03
INTENSITY
NET OVERALL
NEGATIVES
POSITIVES
DONE
1 F & M
33.000 93.74
2
55 000 107.88
3
62.000 94.13
0.8300E+02
10.
FREQ (HZ)
100.
1
2
3

TEST2

P#5 RUMBLE #2

FREQ= 10.000
MAG= 93 33

0.1120E+03
INTENSITY

NET OVERALL

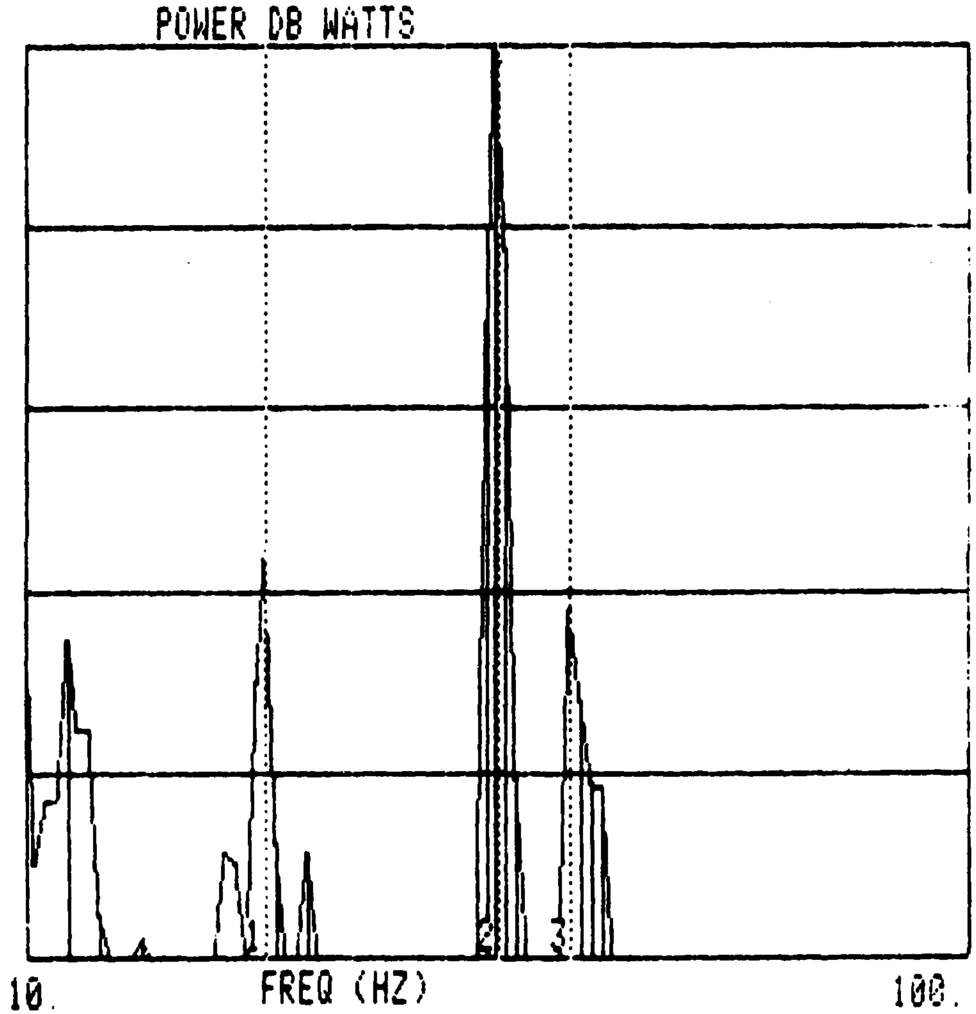
NEGATIVES

POSITIVES

DONE

1 F & M
33.000 94.95
2
55.000 111.93
3
62.000 93.21

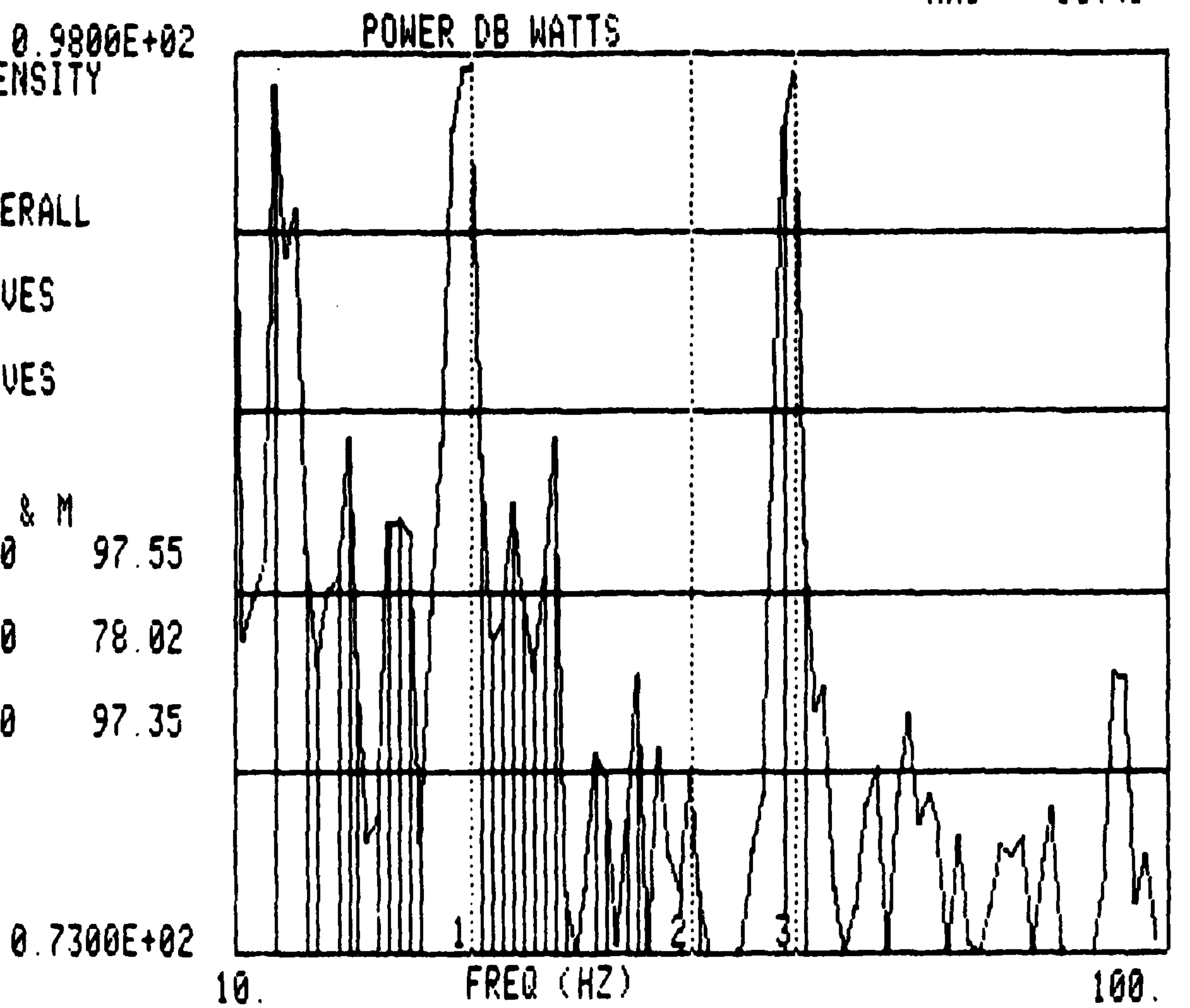
0.8200E+02



TEST2

P#17 NO RUMBLE

FREQ= 10.000
MAG= 95.49



> NET OVERALL

NEGATIVES

POSITIVES

DONE

1	F & M	
33.000		97.55
2		
54.000		78.02
3		
64 000		97.35

TEST2

P#12 NO RUMBLE

FREQ= 10.000
MAG= 93.72

POWER DB WATTS

0.9900E+02
INTENSITY

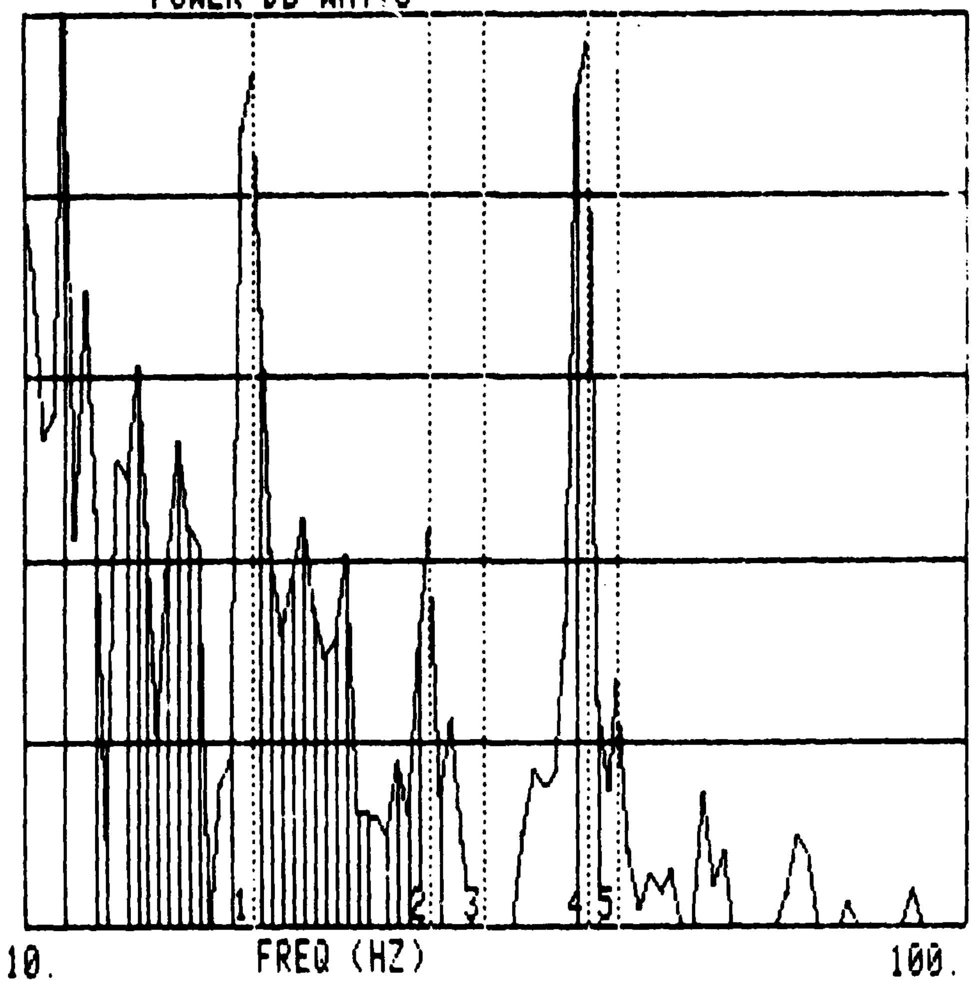
NET OVERALL

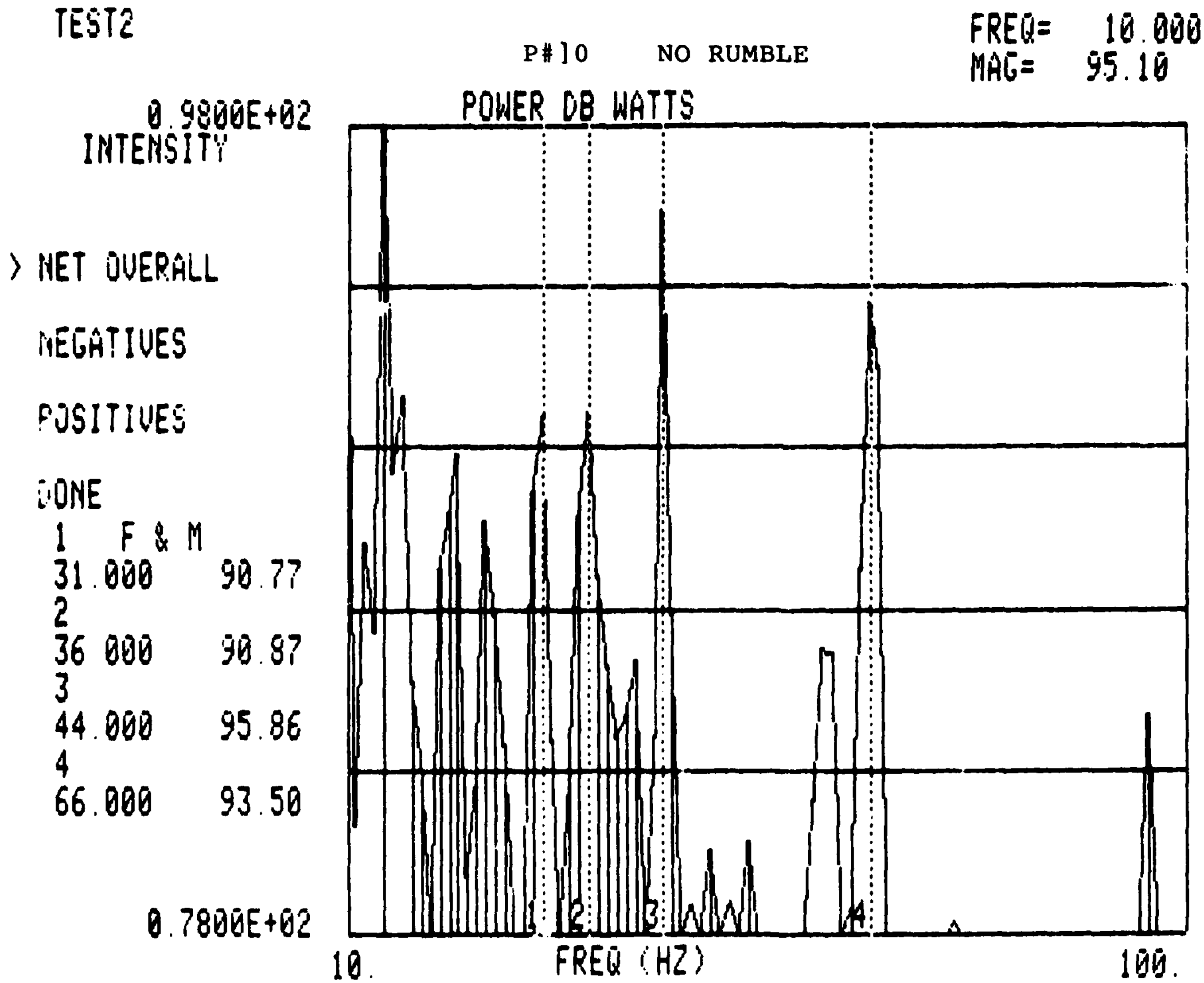
NEGATIVES

POSITIVES

DONE

1 F & M
32.000 97.18
2
49.000 84.57
3
54.000 70.32
4
64.000 98.02
5
67.000 80.57
0.7400E+02



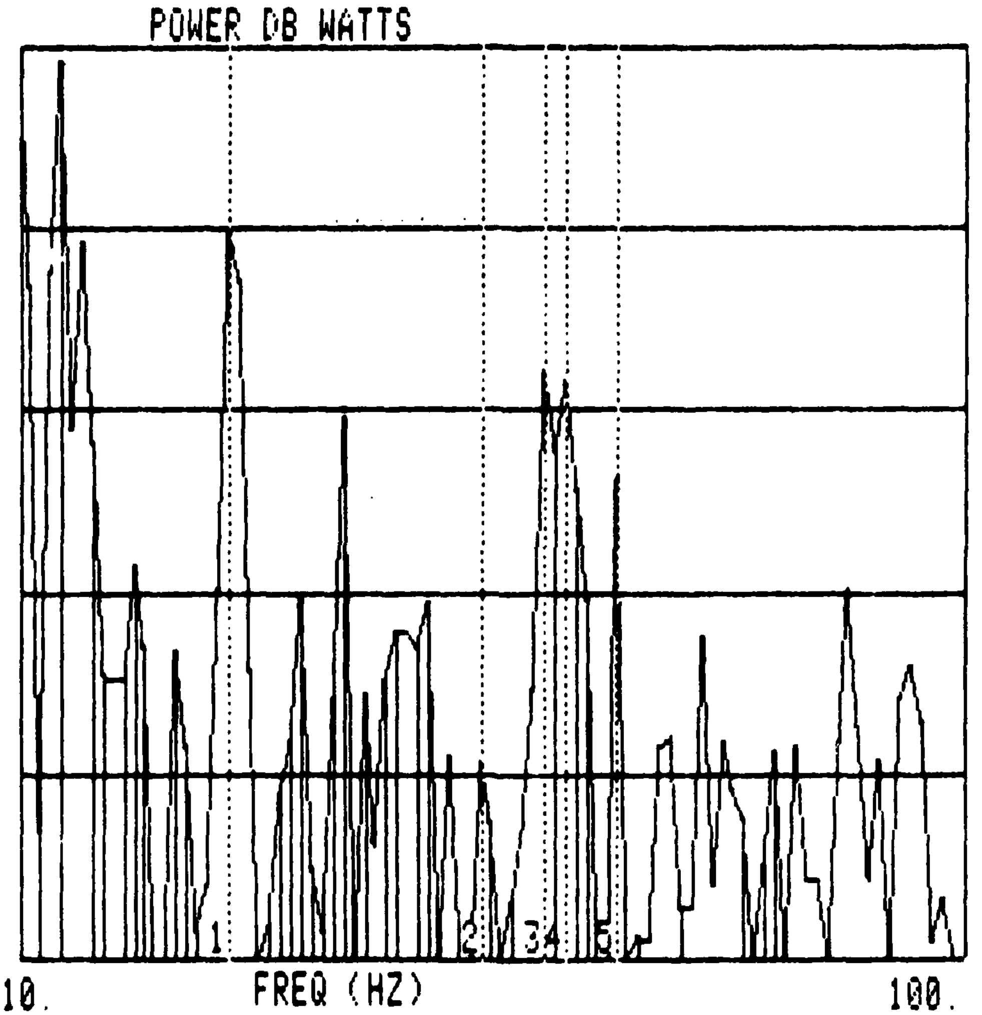

TEST2
P#10 NO RUMBLE
FREQ= 10.000
MAG= 95.10
POWER DB WATTS
0.9800E+02
INTENSITY
> NET OVERALL
NEGATIVES
POSITIVES
DONE
1 F & M
31.000 90.77
2
36 000 90.87
3
44.000 95.86
4
66.000 93.50
0.7800E+02
10.
FREQ (HZ)
100.

TEST2

FREQ= 10.000
MAG= 92.45

P#5 NO RUMBLE

0.9300E+02
INTENSITY



> NET OVERALL

NEGATIVES

POSITIVES

ZONE

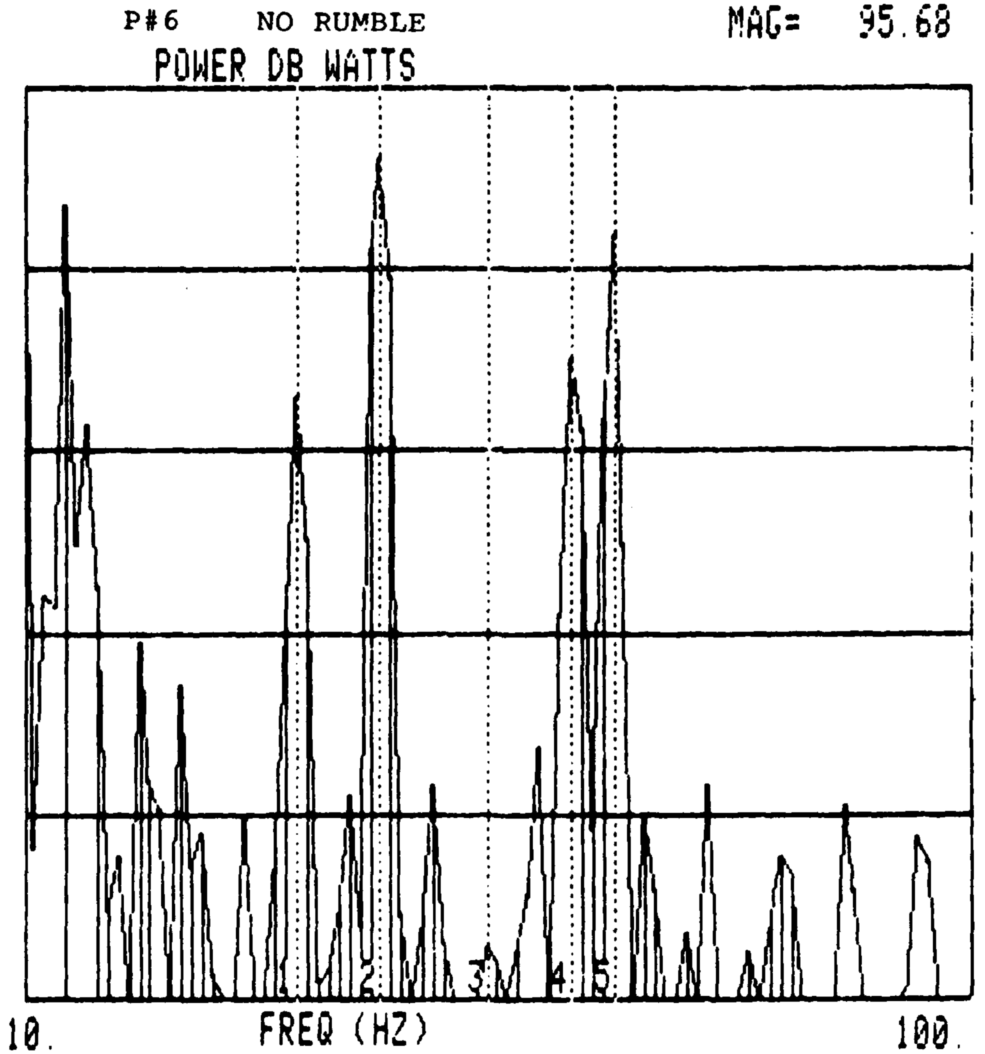
1	F & M	
	30.000	88.87
2		
	54.000	77.26
3		
	60.000	85.87
4		
	62.000	85.66
5		
	67.000	83.46

0.7300E+02

TEST2

FREQ= 10.000
MAG= 95.68

0.9600E+02
INTENSITY



> NET OVERALL

NEGATIVES

POSITIVES

DONE

1	F & M	
	36.000	89.21
2		
	44.000	94.34
3		
	54.000	77.12
4		
	62.000	90.05
5		
	66.000	92.69

0.7600E+02

TEST2

P#17 RUMBLE #2 & #3

FREQ= 10.000
MAG= 106.59

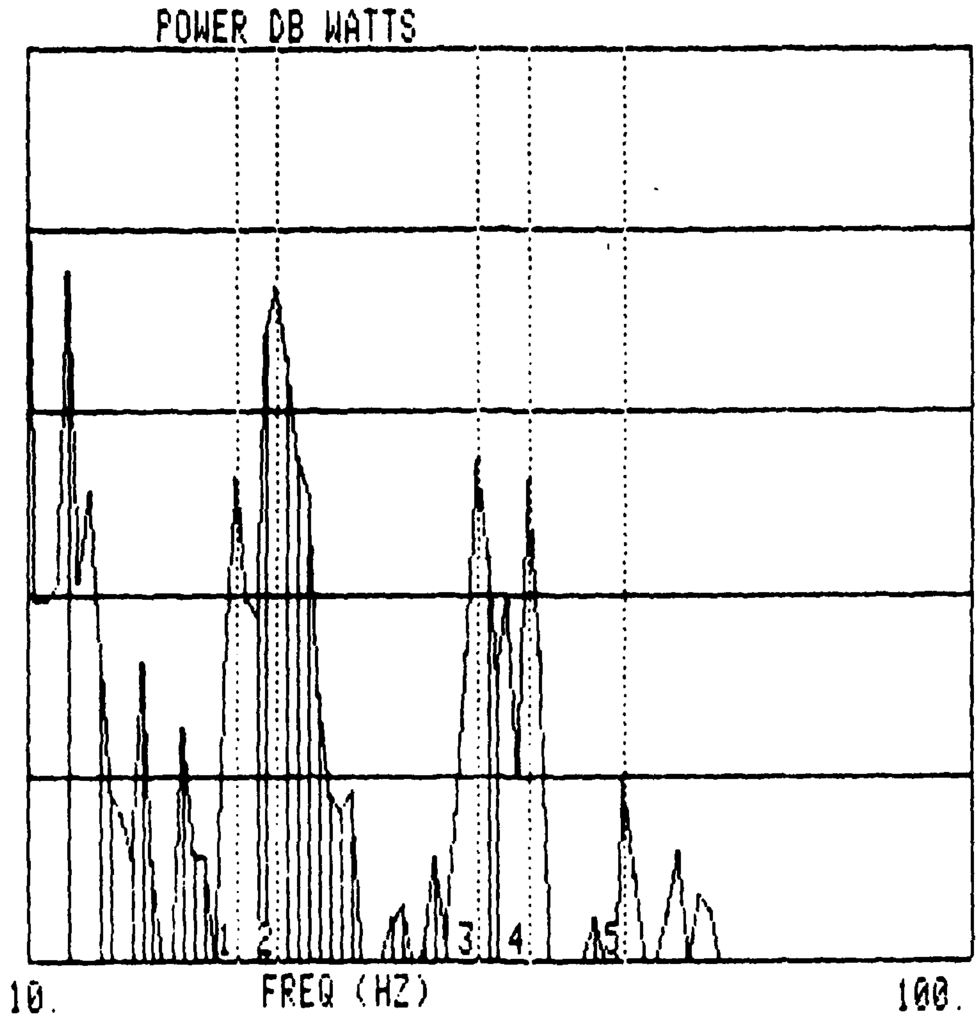
0.1070E+03
INTENSITY

> NET OVERALL

NEGATIVES

POSITIVES

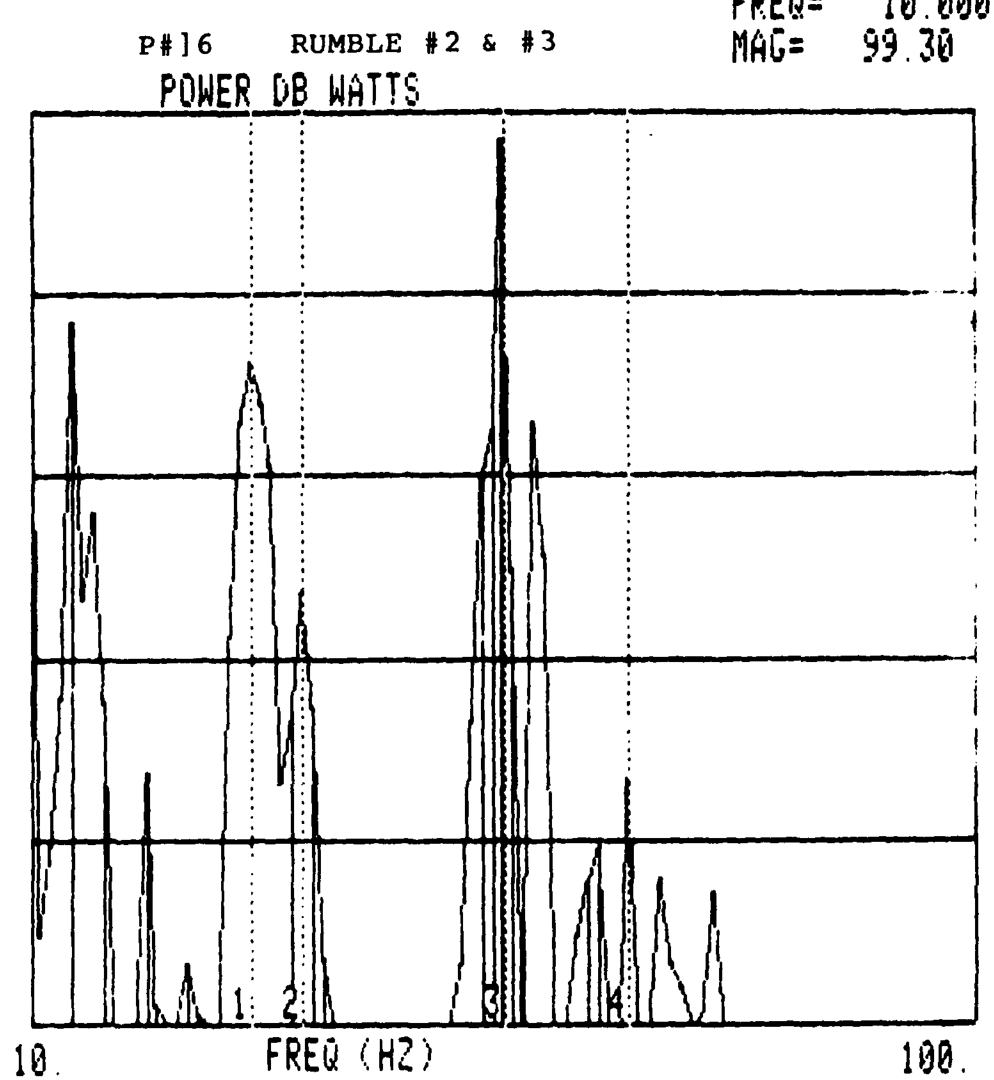
DONE



1	F & M
30.000	95.16
2	
34.000	100.39
3	
53.000	95.57
4	
58.000	95.09
5	
67.000	86.80

0.8200E+02

TEST2



> NET OVERALL

NEGATIVES

-+POSITIVES

TONE

TONE	F	M
1	31.000	98.42
2	36.000	93.36
3	55.000	103.19
4	67.000	89.25

P 15

TEST2

FREQ= 10.000
MAG= 101.23

P#15 RUMBLE #2 & #3

POWER DB WATTS

0.1020E+03
INTENSITY

> NET OVERALL

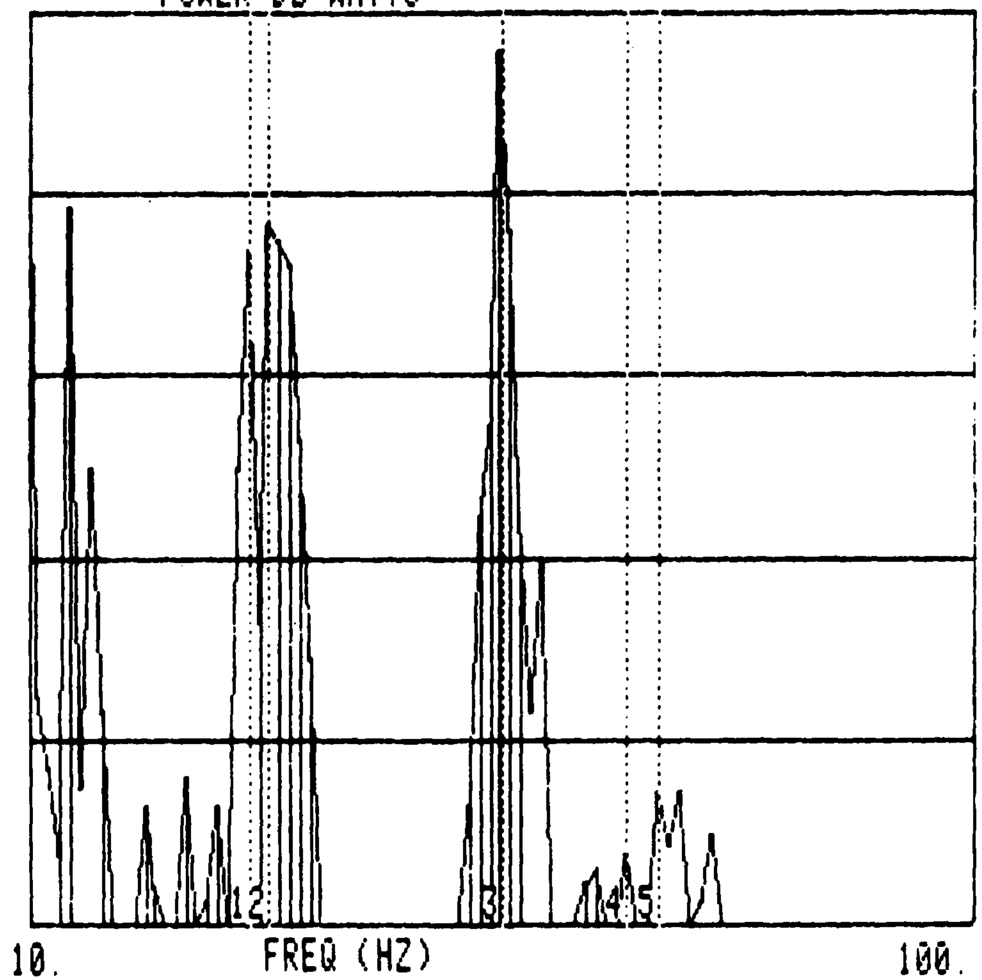
NEGATIVES

POSITIVES

ZONE

1	F & M	
	31.000	96.70
2		
	33.000	97.19
3		
	55.000	101.06
4		
	67.000	83.53
5		
	70.000	84.80

0.8200E+02



TEST2

P#14 RUMBLE #2 & #3

FREQ= 10.000
MAG= 101.34

0.1070E+03
INTENSITY

NET OVERALL

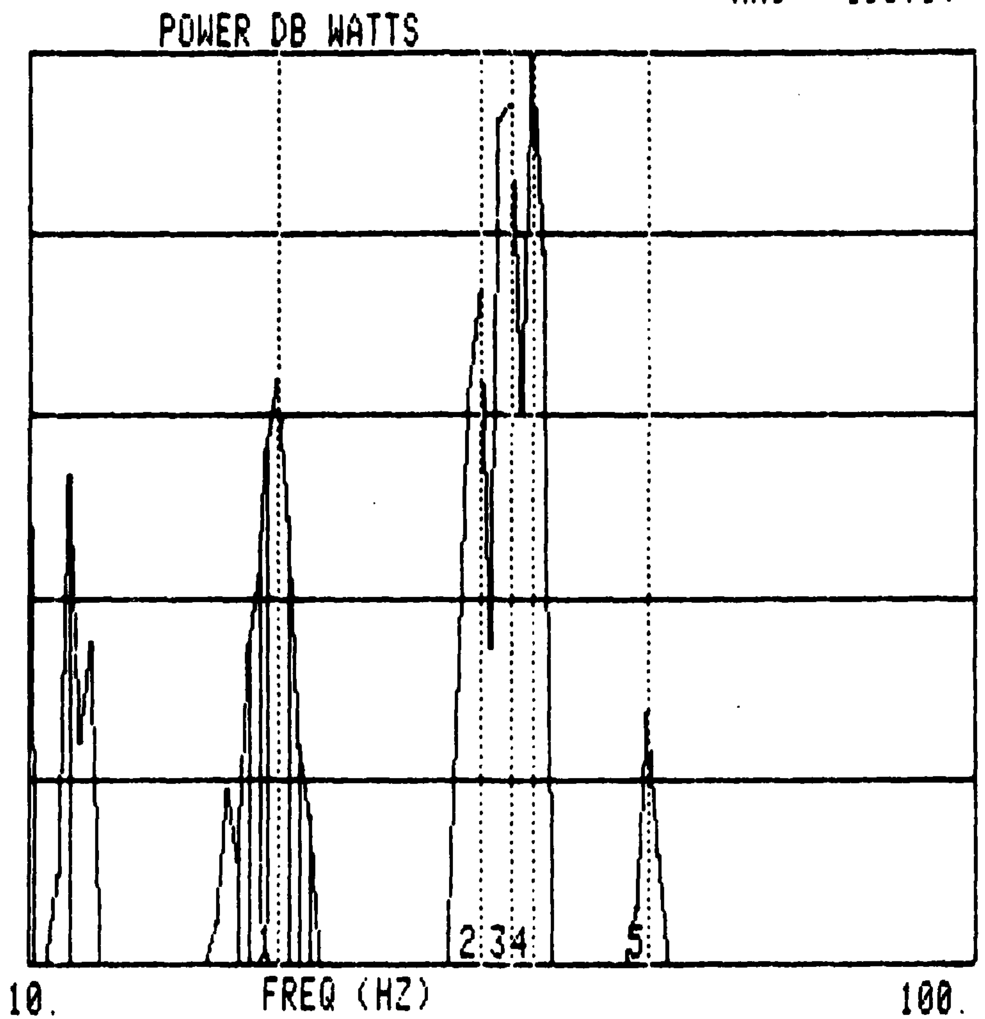
NEGATIVES

POSITIVES

DONE

1	F & M	
	34.000	99.77
2		
	53.000	101.51
3		
	56.000	105.81
4		
	58.000	106.78
5		
	69.000	92.36

0.8700E+02



TEST2

FREQ= 10.000
MAG= 101.76

P#13 RUMBLE #2 & #3

POWER DB WATTS

0.1040E+03
INTENSITY

NET OVERALL

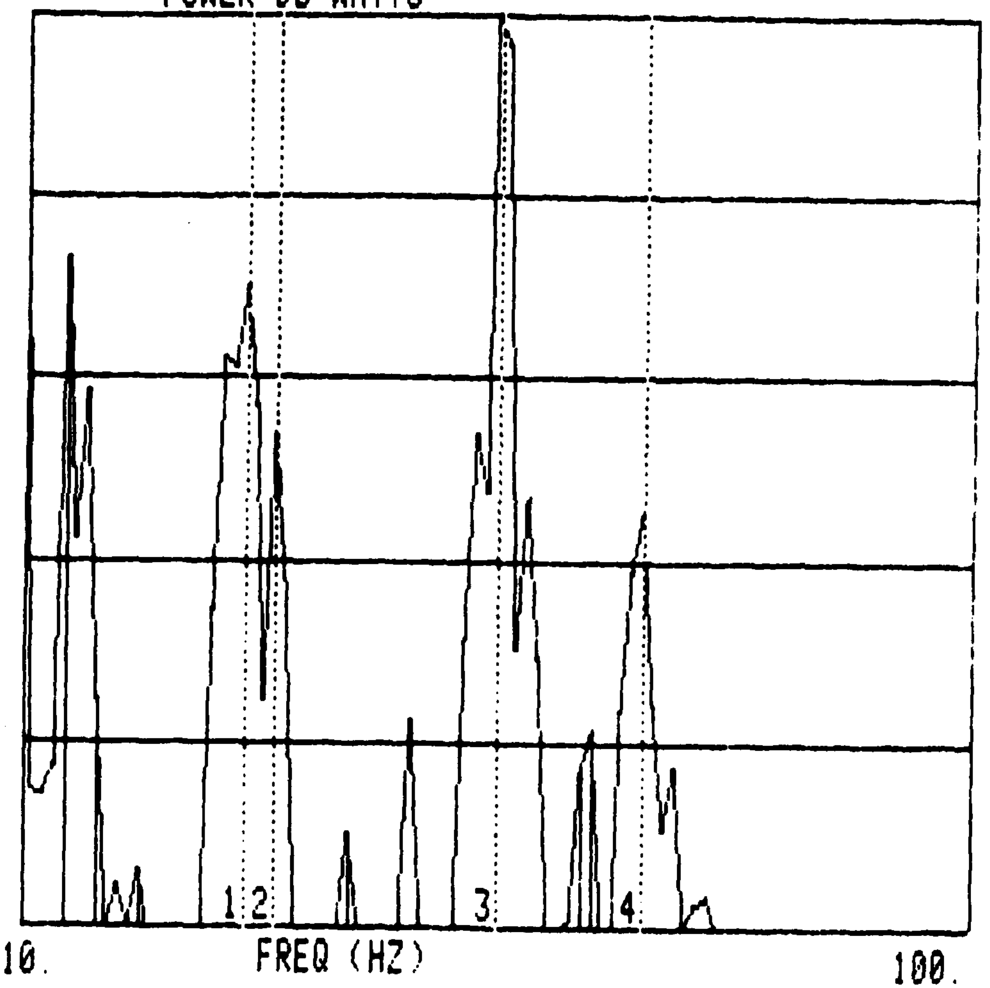
NEGATIVES

POSITIVES

DONE

1	F & M	
31.000		97.89
2		
34.000		94.69
3		
55.000		103.95
4		
69.000		92.96

0.8400E+02



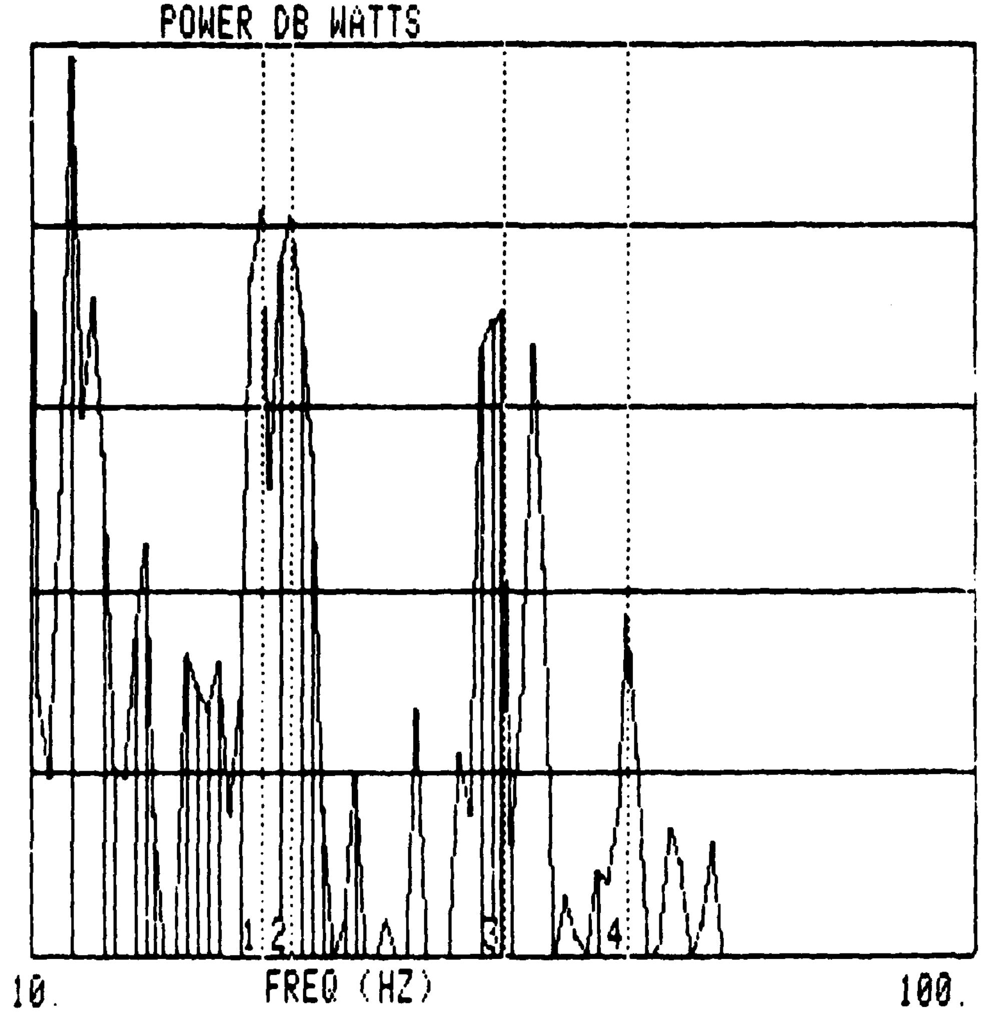
TEST2

FREQ= 10.000
MAG= 98.46

P#12 RUMBLE #2 & #3

POWER DB WATTS

0.1000E+03
INTENSITY



0.9000E+02

NET OVERALL

NEGATIVES

POSITIVES

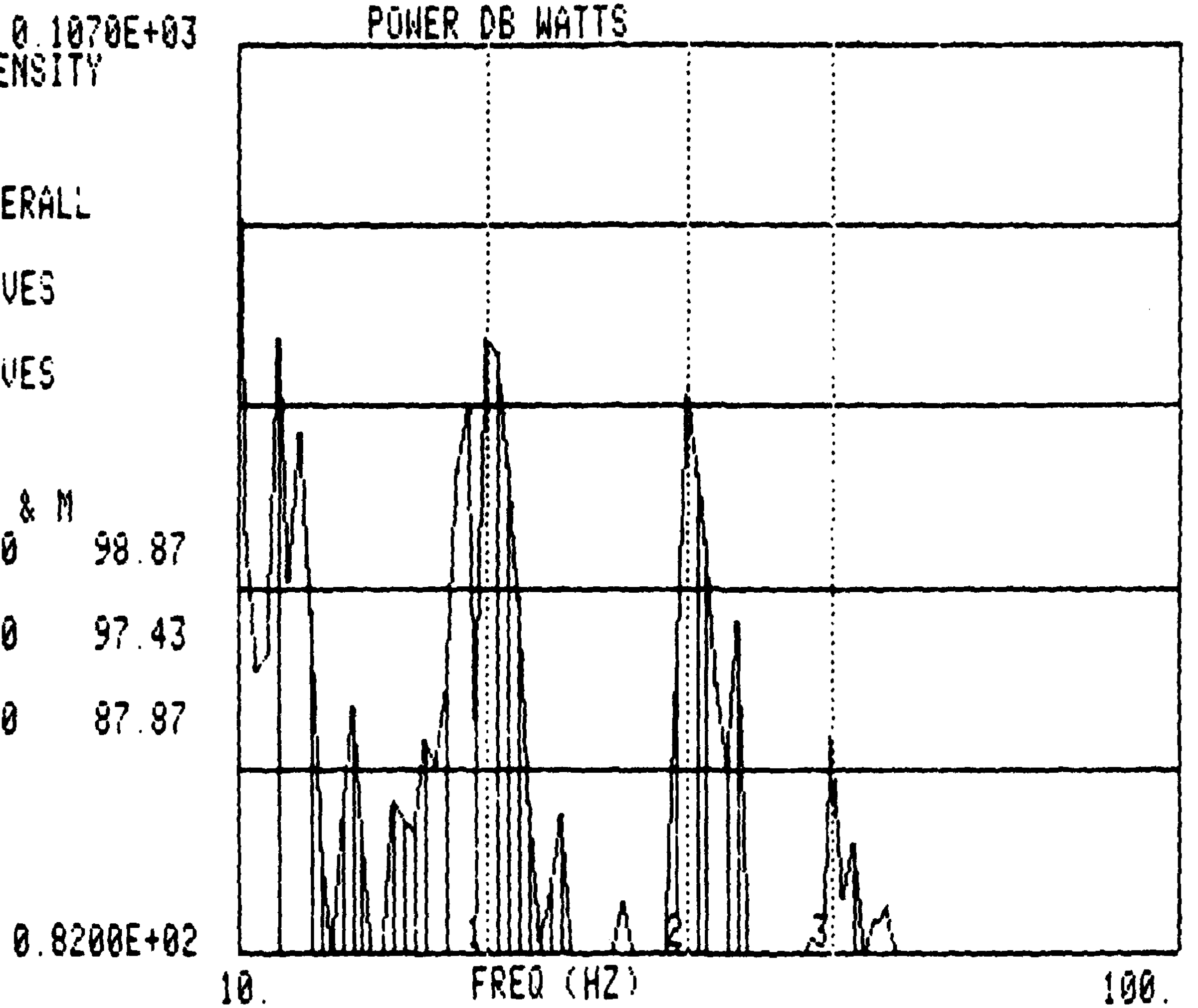
DONE

1	F & M	
32.000		96.29
2		
35.000		96.20
3		
55.000		94 11
4		
67.000		87 41

TEST2

FREQ= 10.000
MAG= 106.54

P#10 RUMBLE #2 & #3



> NET OVERALL

NEGATIVES

POSITIVES

DONE

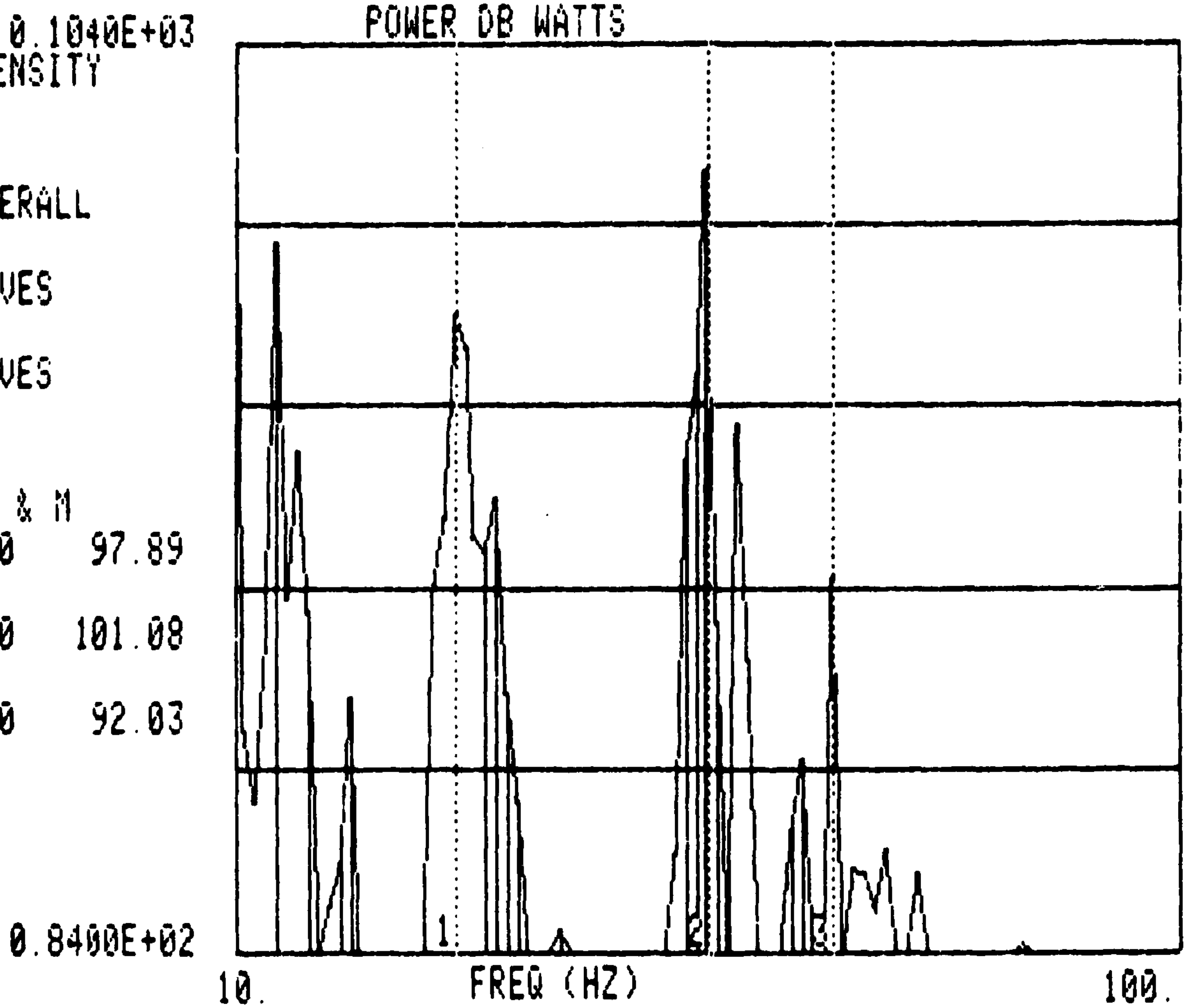
	F & M
1	
34.000	98.87
2	
53.000	97.43
3	
67.000	87.87

TEST2

P#9 RUMBLE #3 & #4

FREQ= 10.000
MAG= 103.01

POWER DB WATTS



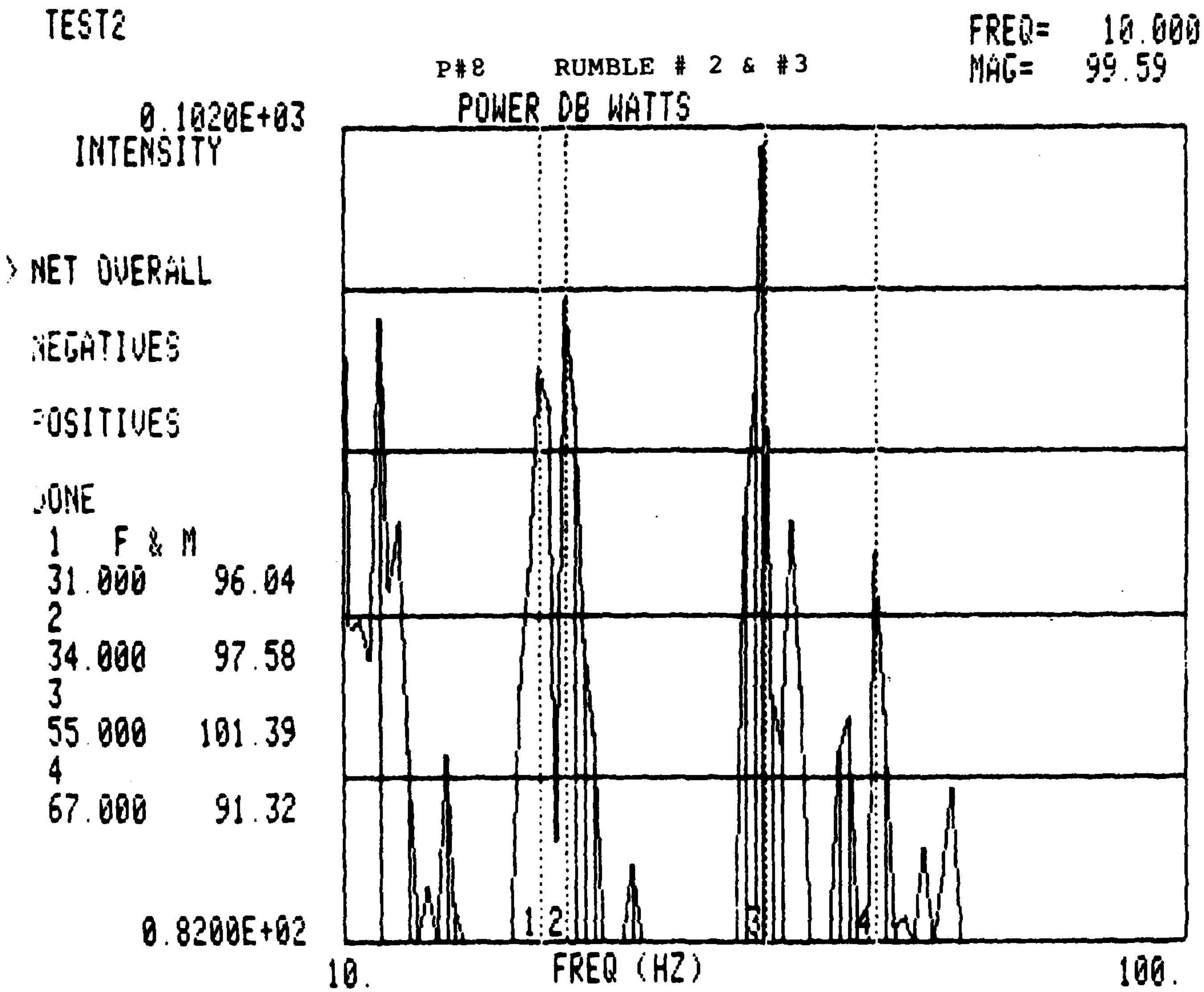
> NET OVERALL

NEGATIVES

POSITIVES

DONE

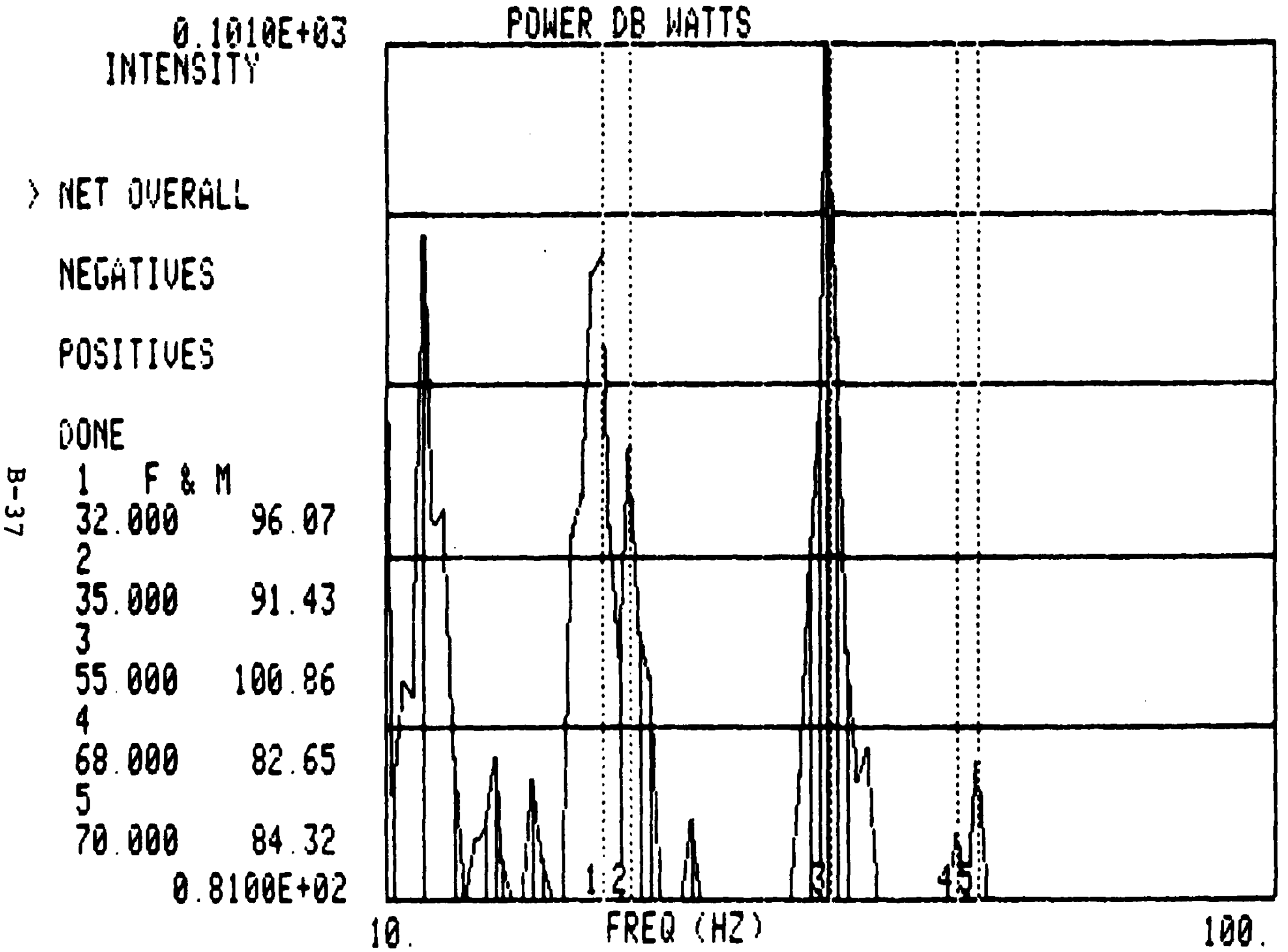
1 F & M
31.000 97.89
2
55.000 101.08
3
67.000 92.03


TEST2
P#8 RUMBLE # 2 & #3
POWER DB WATTS
FREQ= 10.000
MAG= 99.59
0.1020E+03
INTENSITY
> NET OVERALL
NEGATIVES
POSITIVES
DONE
1 F & M
31.000 96.04
2
34.000 97.58
3
55.000 101.39
4
67.000 91.32
0.8200E+02
10.
FREQ (HZ)
100.
1
2
3
4

TEST2

P#7 RUMBLE #2 & #3

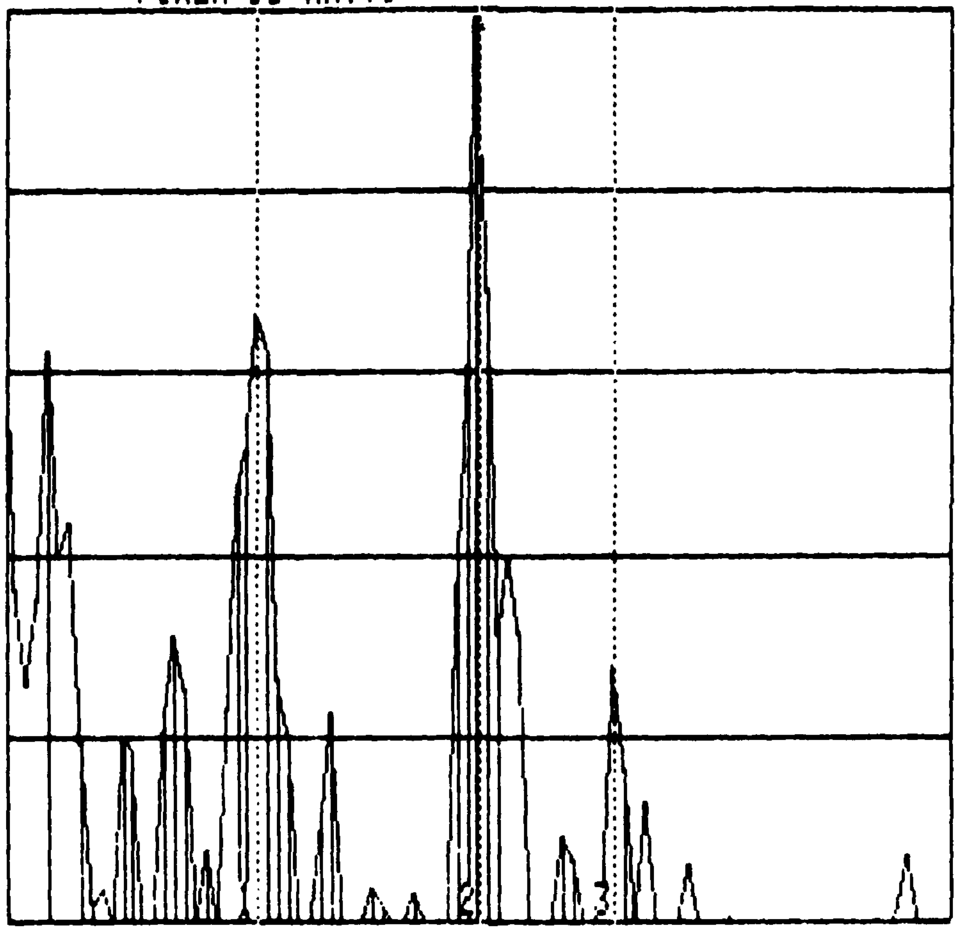
FREQ= 10.000
MAG= 96.51



TEST2

P#5 RUMBLE #2 & #3

FREQ= 10.000
MAG= 93.54



> NET OVERALL

NEGATIVES

POSITIVES

DONE

1 F & M
34.000 94.53
2
55.000 102.65
3
68.000 84.92

TEST2

FREQ= 10.000
MAG= 96.02

P#6 RUMBLE #2 & #3

POWER DB WATTS

0.9800E+02
INTENSITY

> NET OVERALL

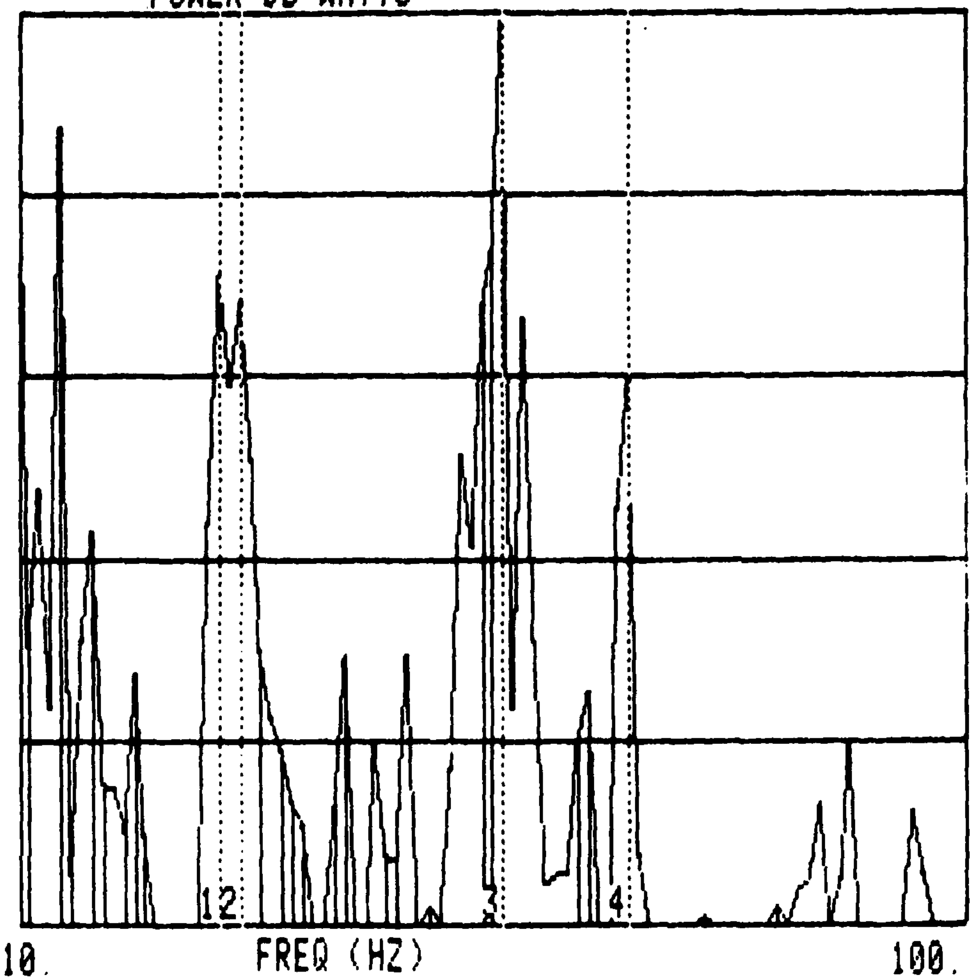
NEGATIVES

POSITIVES

DONE

	F & M	
1	29.000	92.23
2	31.000	91.61
3	56.000	97.67
4	68.000	89.86

0.7800E+02



TEST2

P#5 RUMBLE #2 & #3

BLEED AIR ON

FREQ= 10.000
MAG= 100.79

POWER DB WATTS

0.1060E+03
INTENSITY

> NET OVERALL

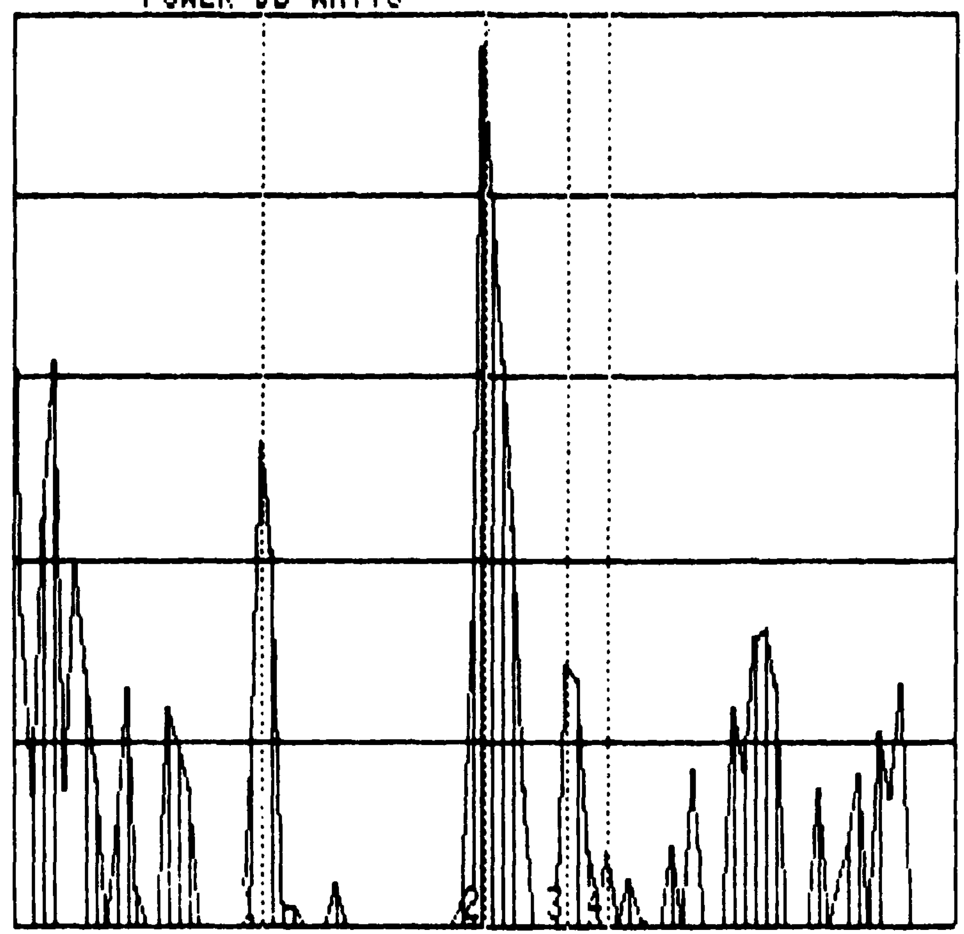
NEGATIVES

POSITIVES

DONE

1	F & M	
	34.000	96.57
2		
	55.000	105.17
3		
	63.000	91.67
4		
	67.000	87.62

0.8600E+02



10. FREQ (HZ) 100.

TEST2

P#4 RUMBLE #2 & #3

BLEED AIR ON

FREQ= 10.000
MAG= 102.59

POWER DB WATTS

0.1030E+03
INTENSITY

NET OVERALL

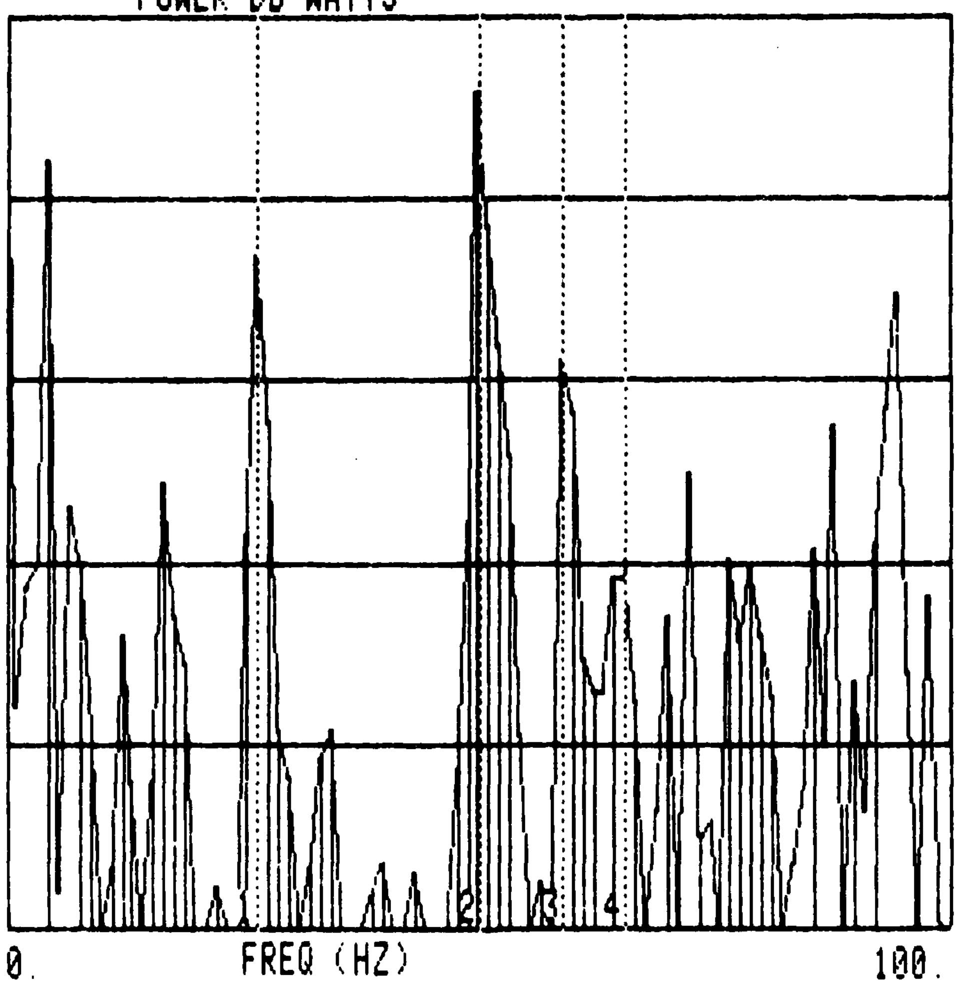
NEGATIVES

POSITIVES

DONE

1 F & M
34.000 97.68
2
55.000 101.21
3
63.000 95.40
4
69.000 90.77

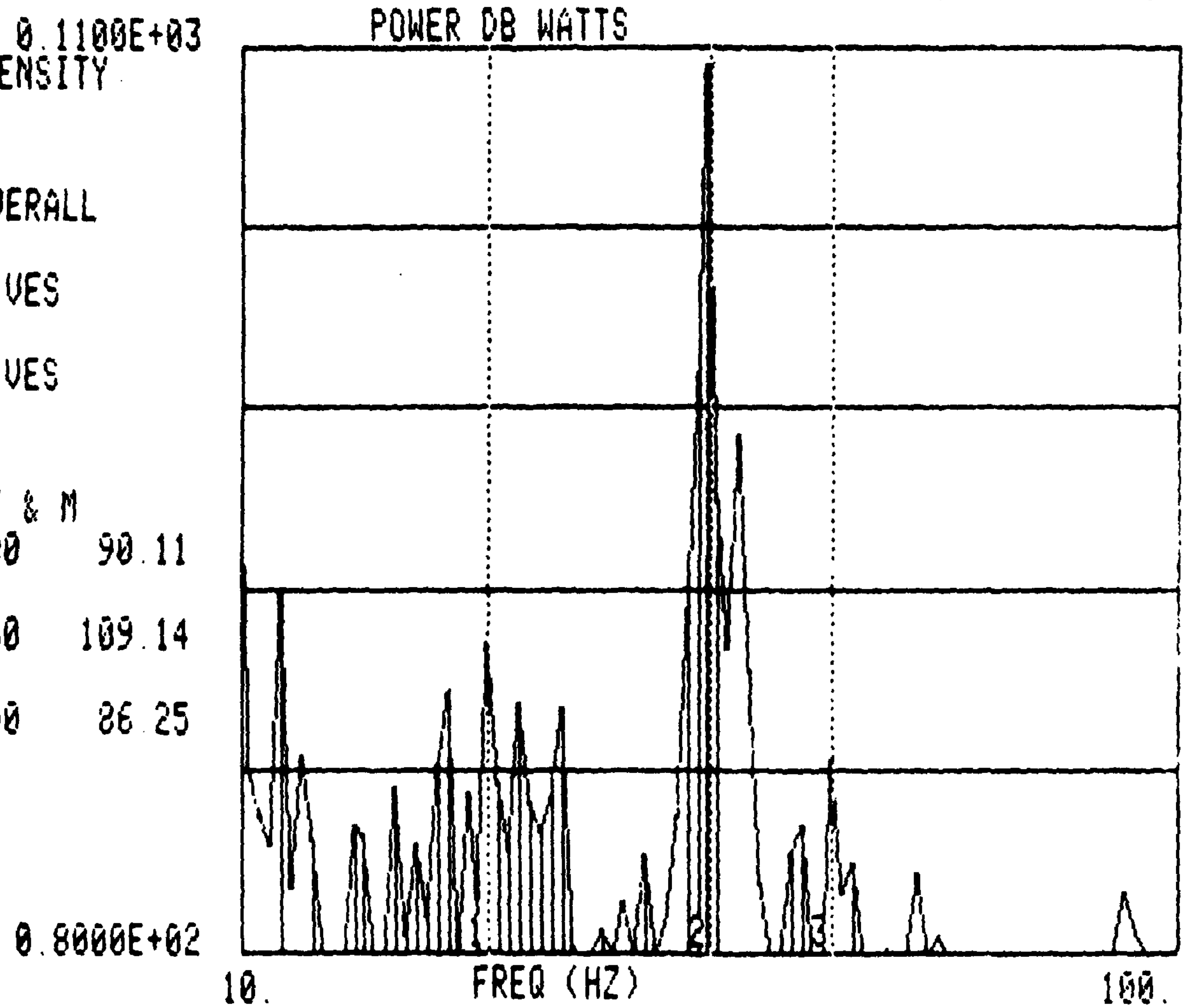
0.8300E+02



TEST2

P#3 RUMBLE #2 & #3

FREQ= 10.000
MAG= 96.06



> NET OVERALL

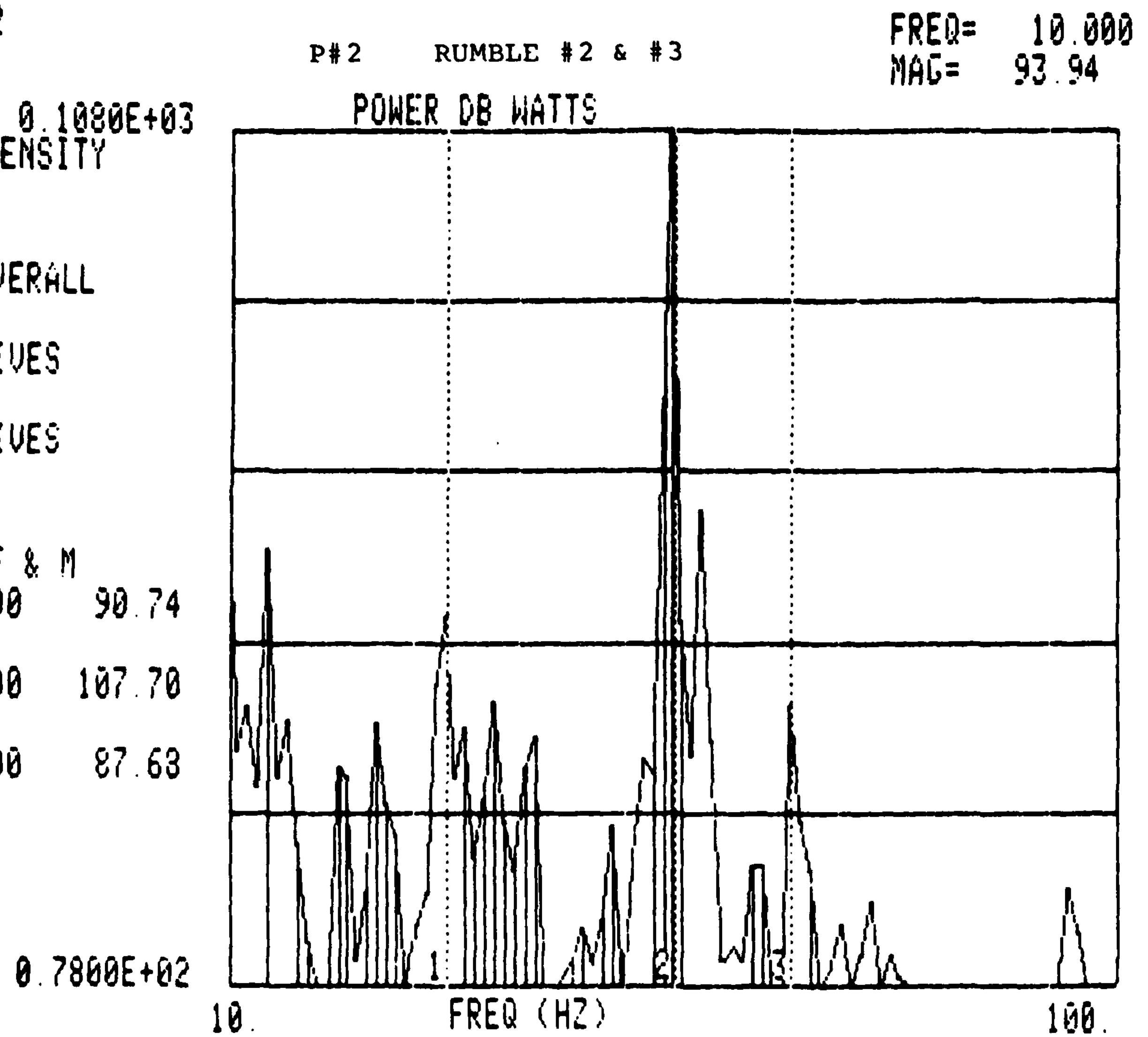
NEGATIVES

POSITIVES

DONE

1 F & M
34.000 90.11
2
55.000 109.14
3
67.000 86.25

TEST2



> NET OVERALL

NEGATIVES

POSITIVES

DONE

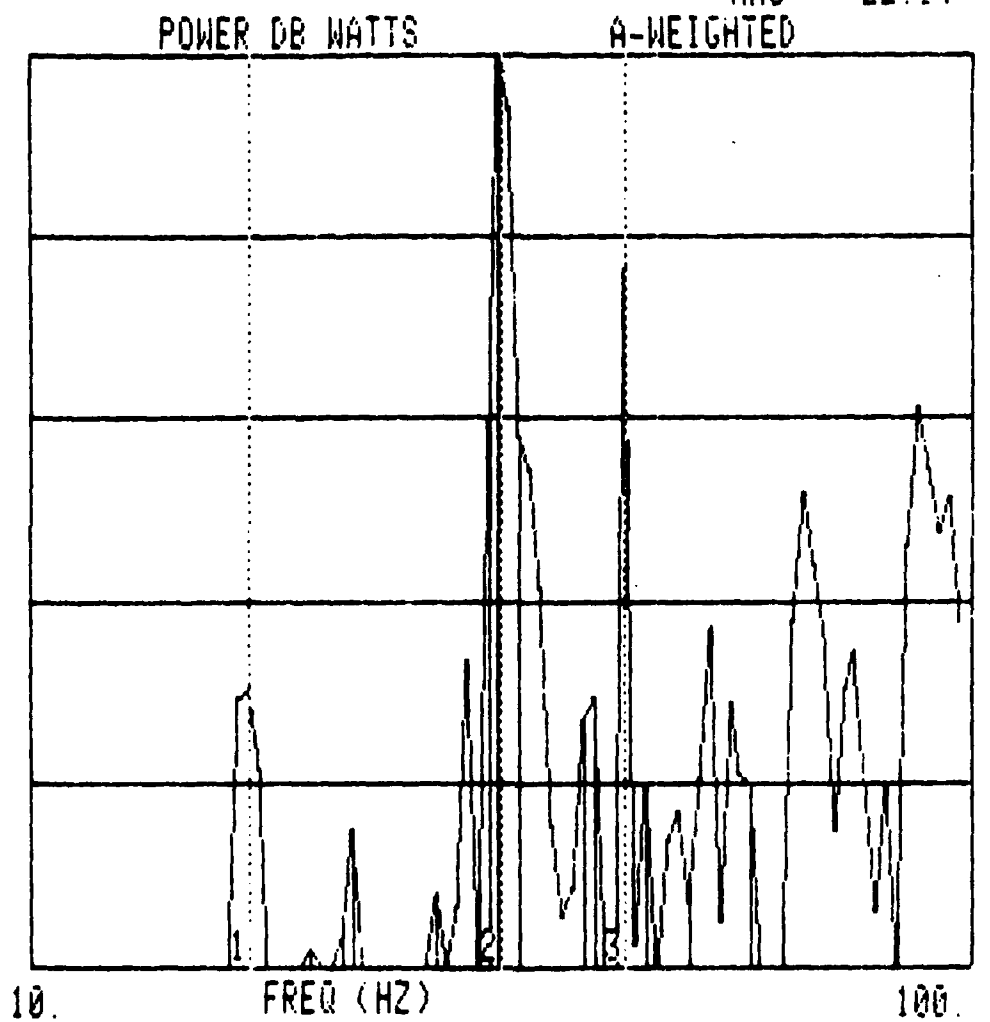
1 F & M
32.000 90.74
2
55.000 107.70
3
67.000 87.63

TEST2

P#] RUMBLE #2 & #3

FREQ= 10.000
MAG= 22.04

0.7000E+02
INTENSITY



0.5000E+02

> NET OVERALL

NEGATIVES

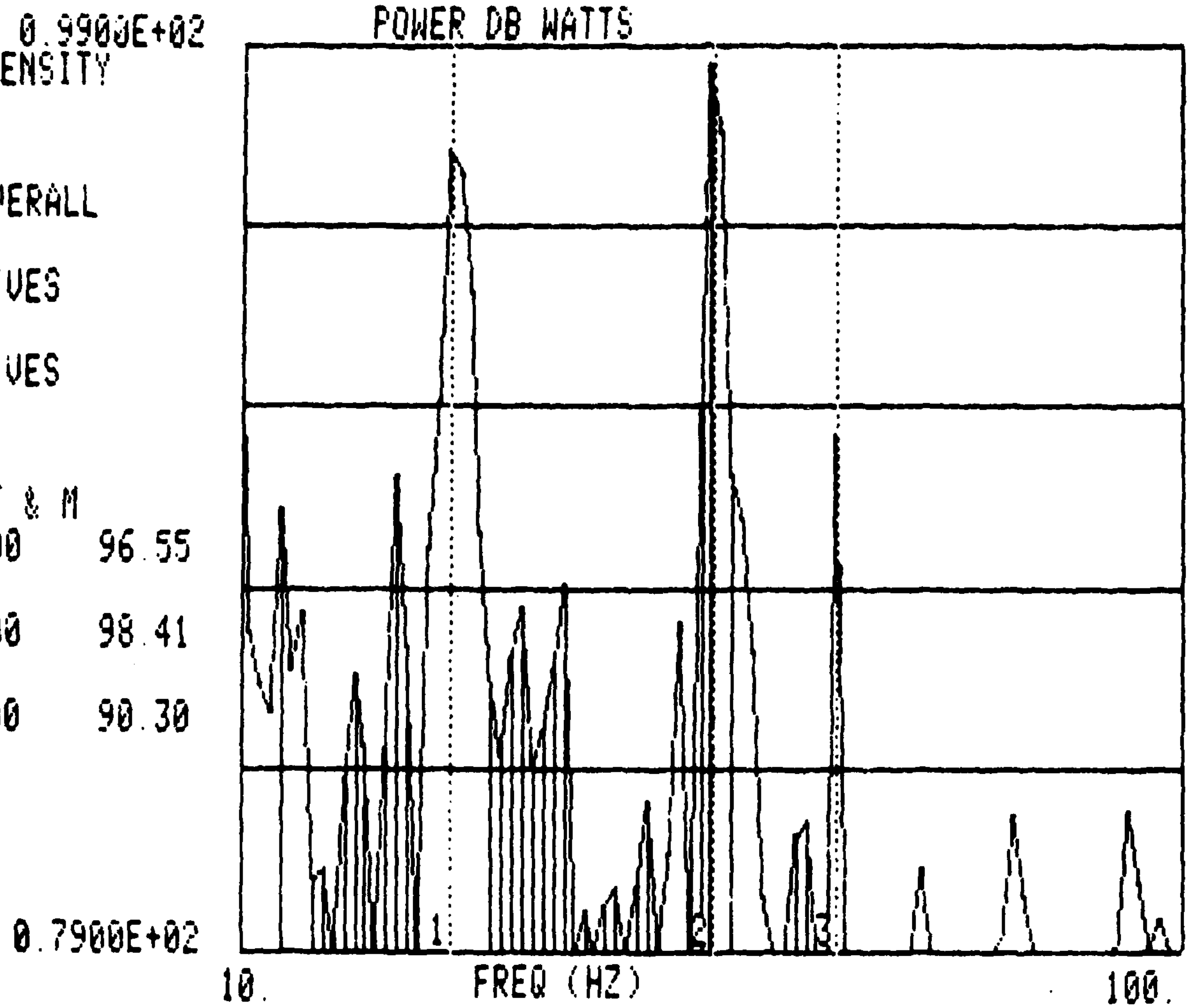
POSITIVES

DONE
1 F & M
31.000 56.06
2
55.000 69.91
3
67.000 65.17

TEST2

P#1 RUMBLE #2 & #3

FREQ= 10.000
MAG= 92.44



> NET OVERALL

NEGATIVES

POSITIVES

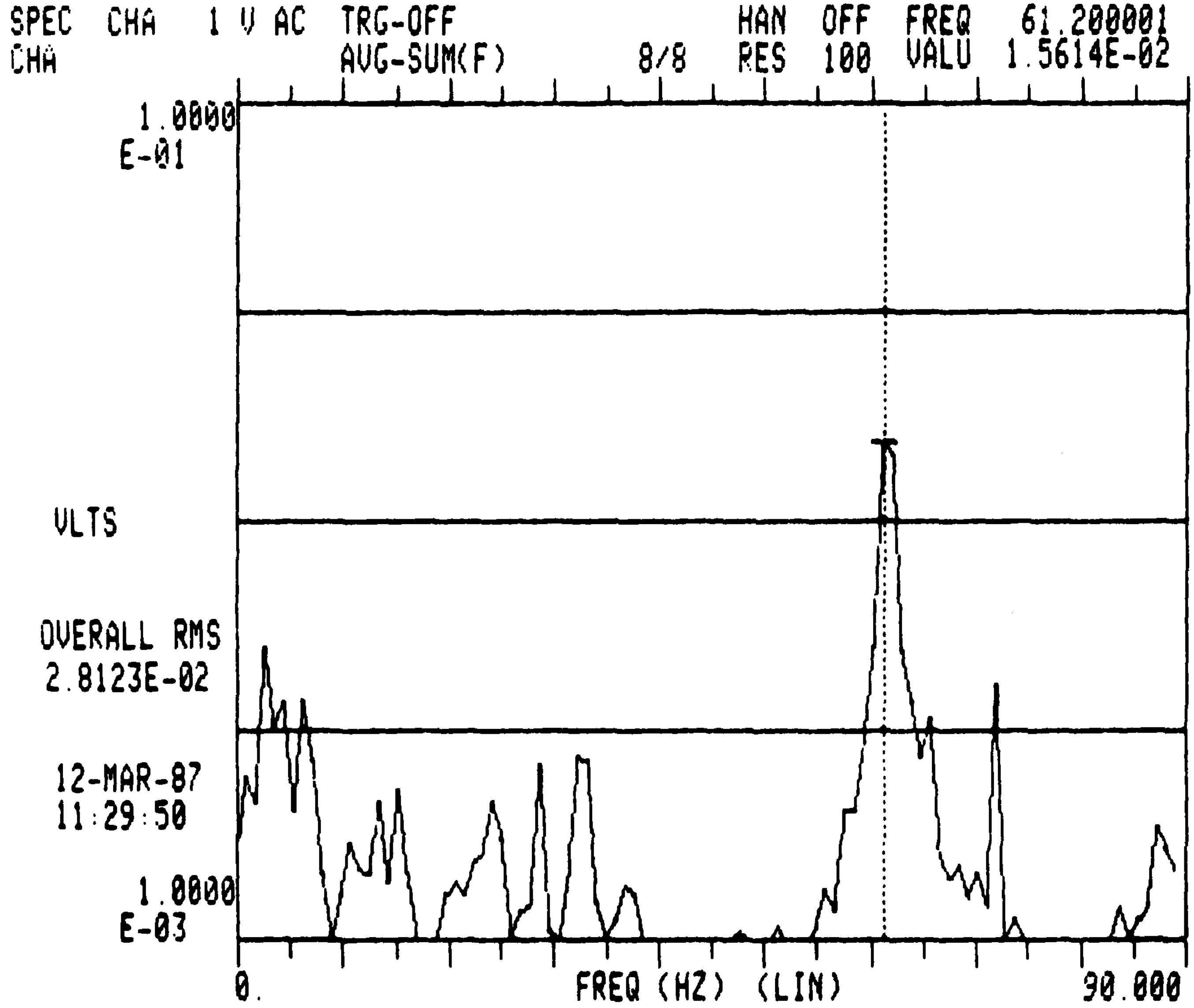
DONE

1	F & M
30.000	96.55
2	
55.000	98.41
3	
67.000	90.30

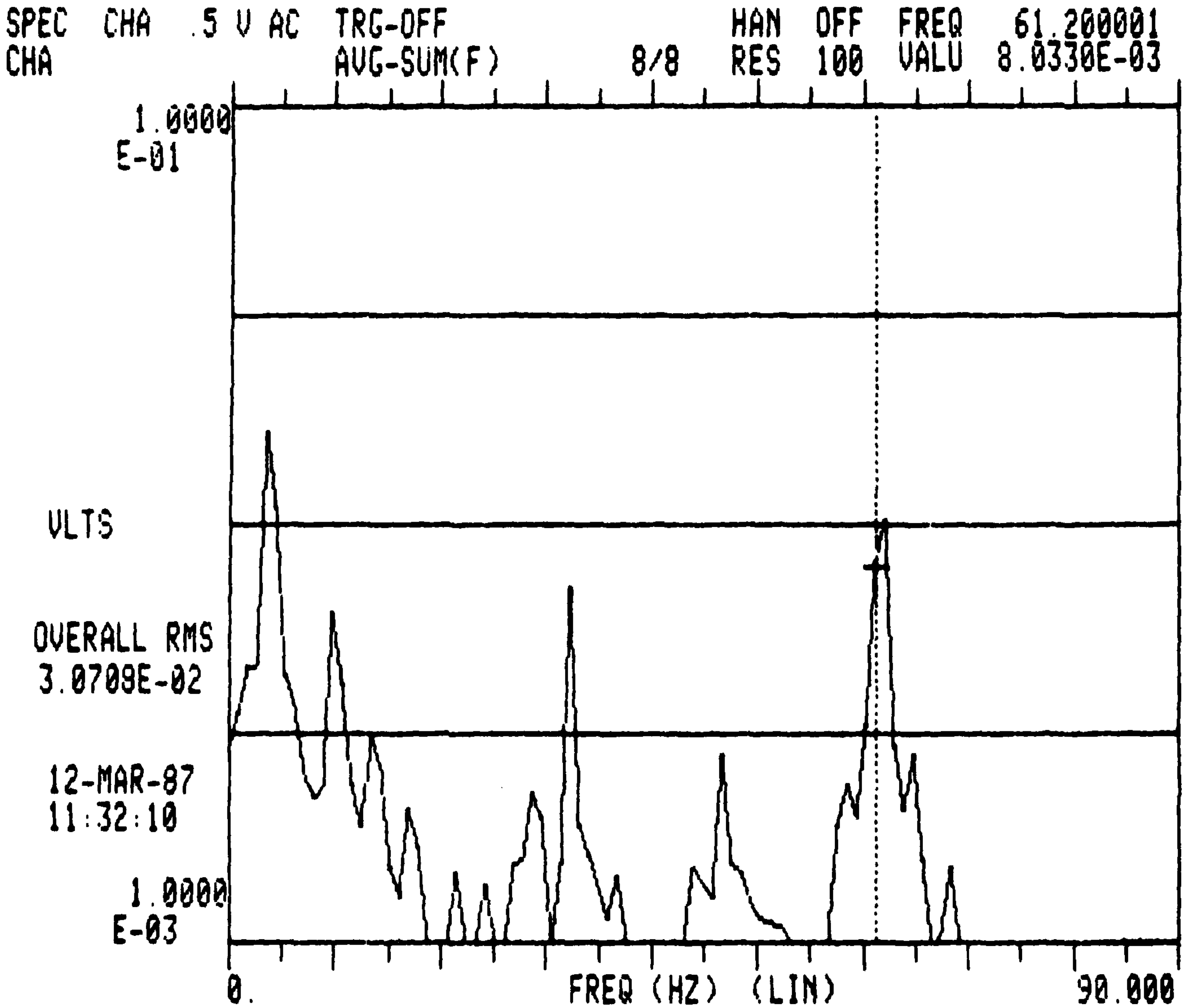
APPENDIX C

DATA POINTS FOR THIRD FLIGHT

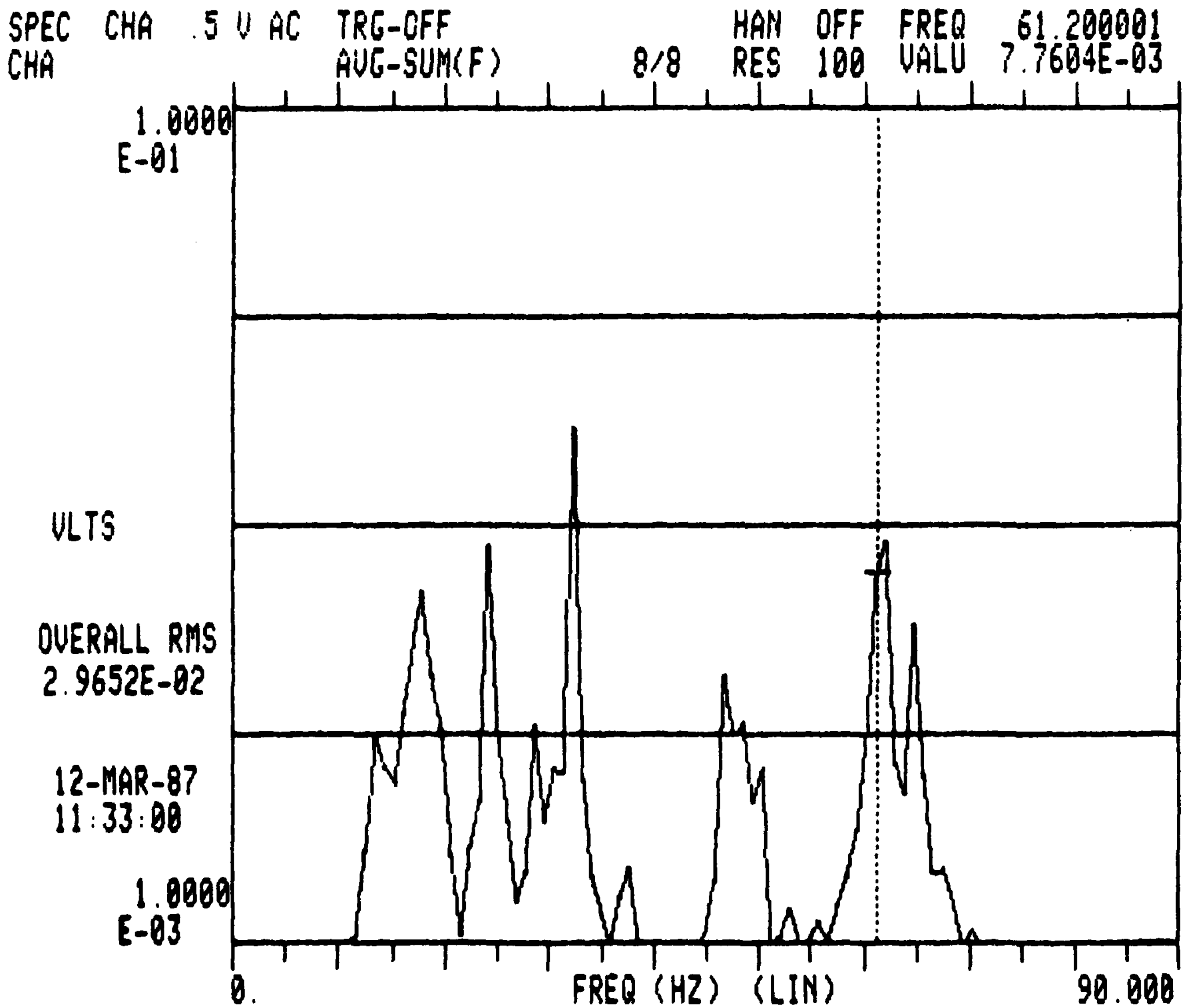
P#2N NO RUMBLE



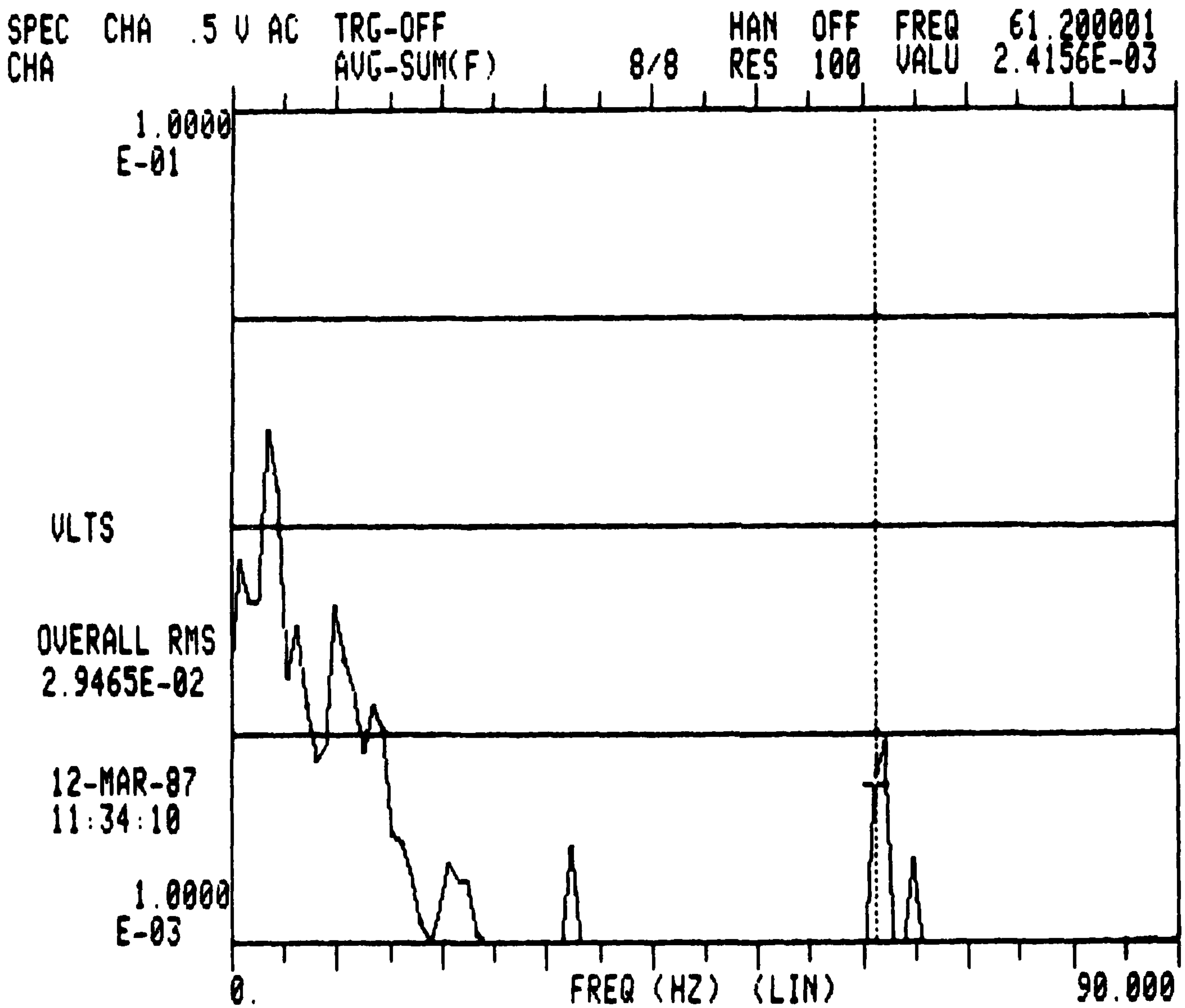
P#12N NO RUMBLE

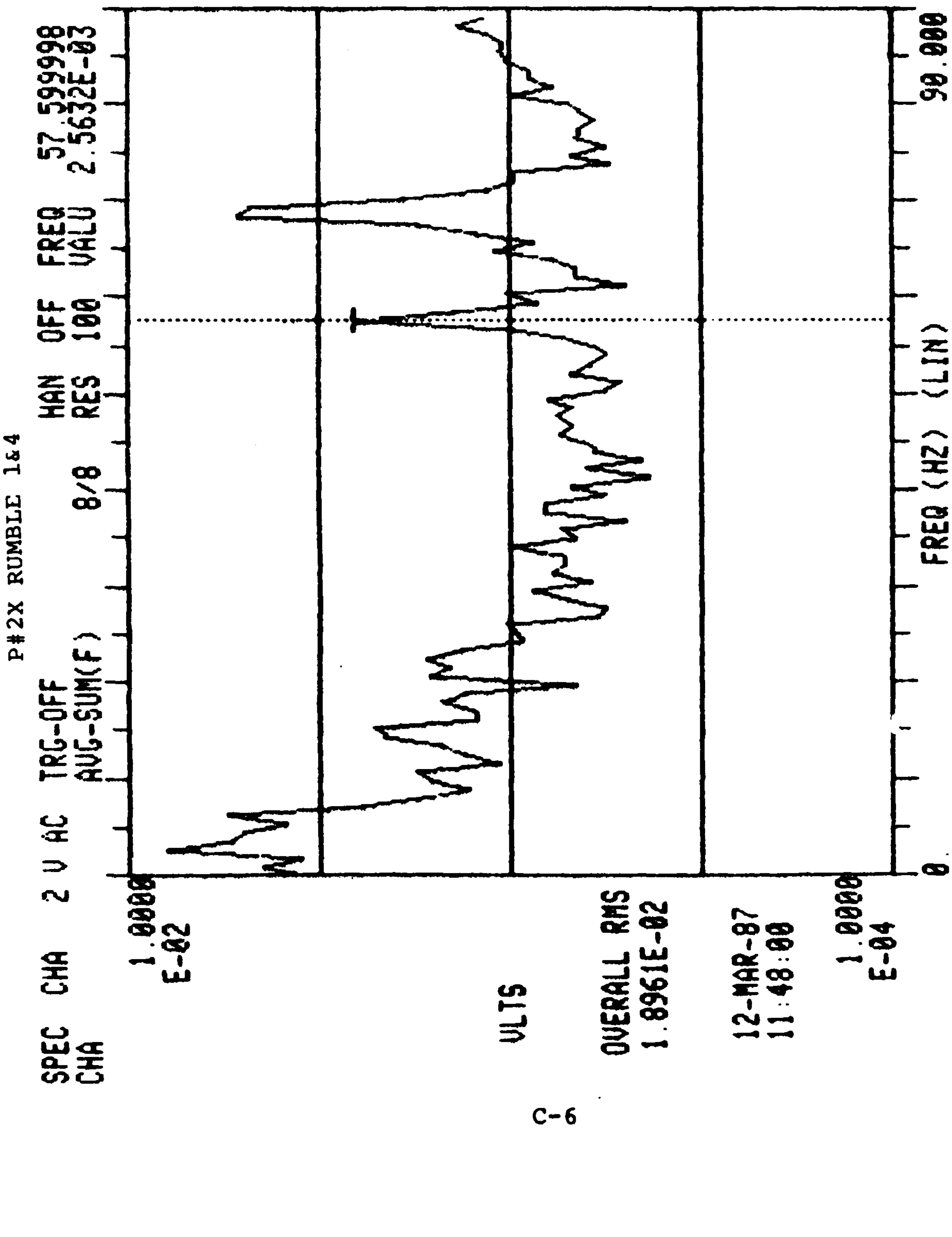


P#13N NO RUMBLE



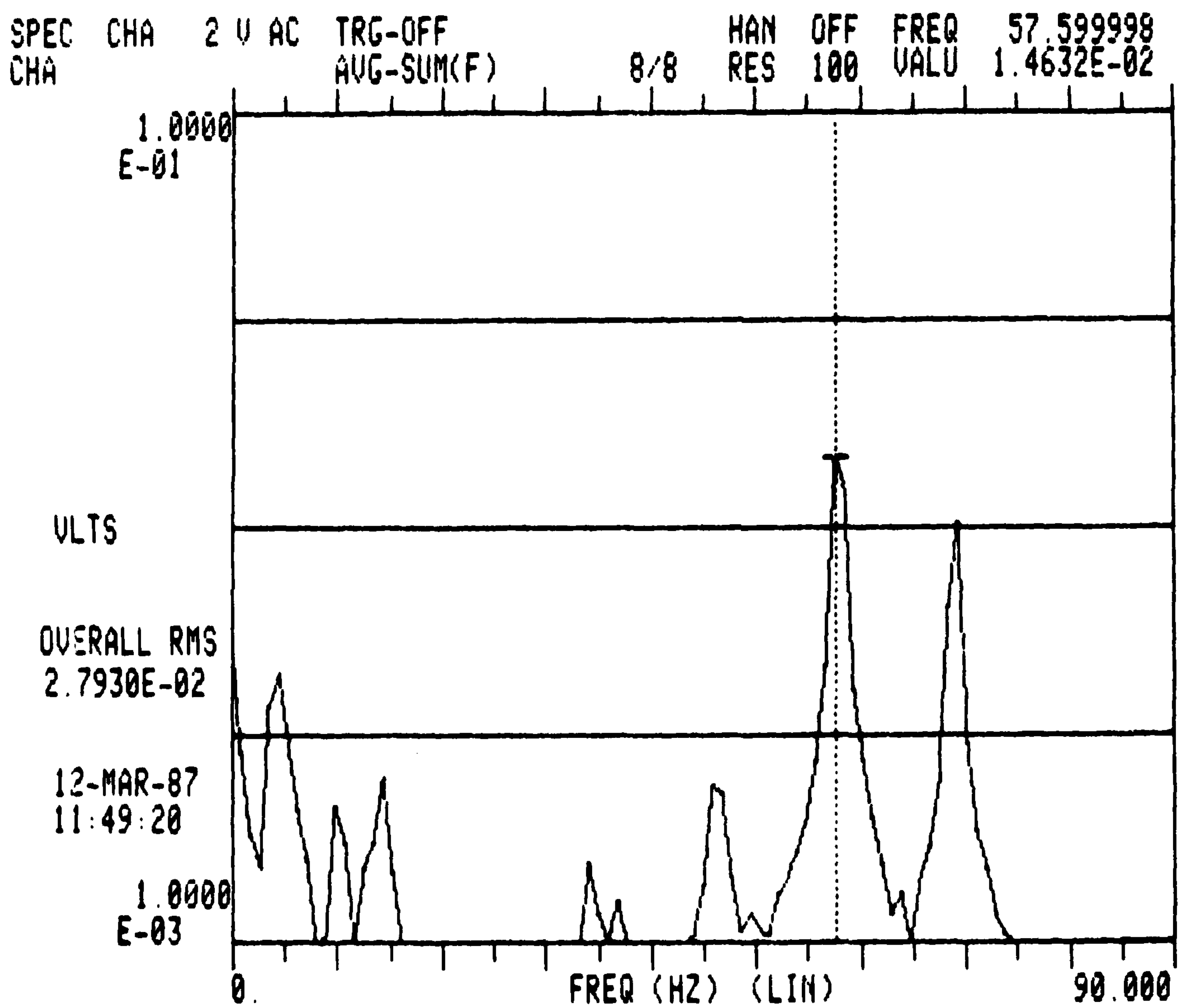
P#]4N NO RUMBLE

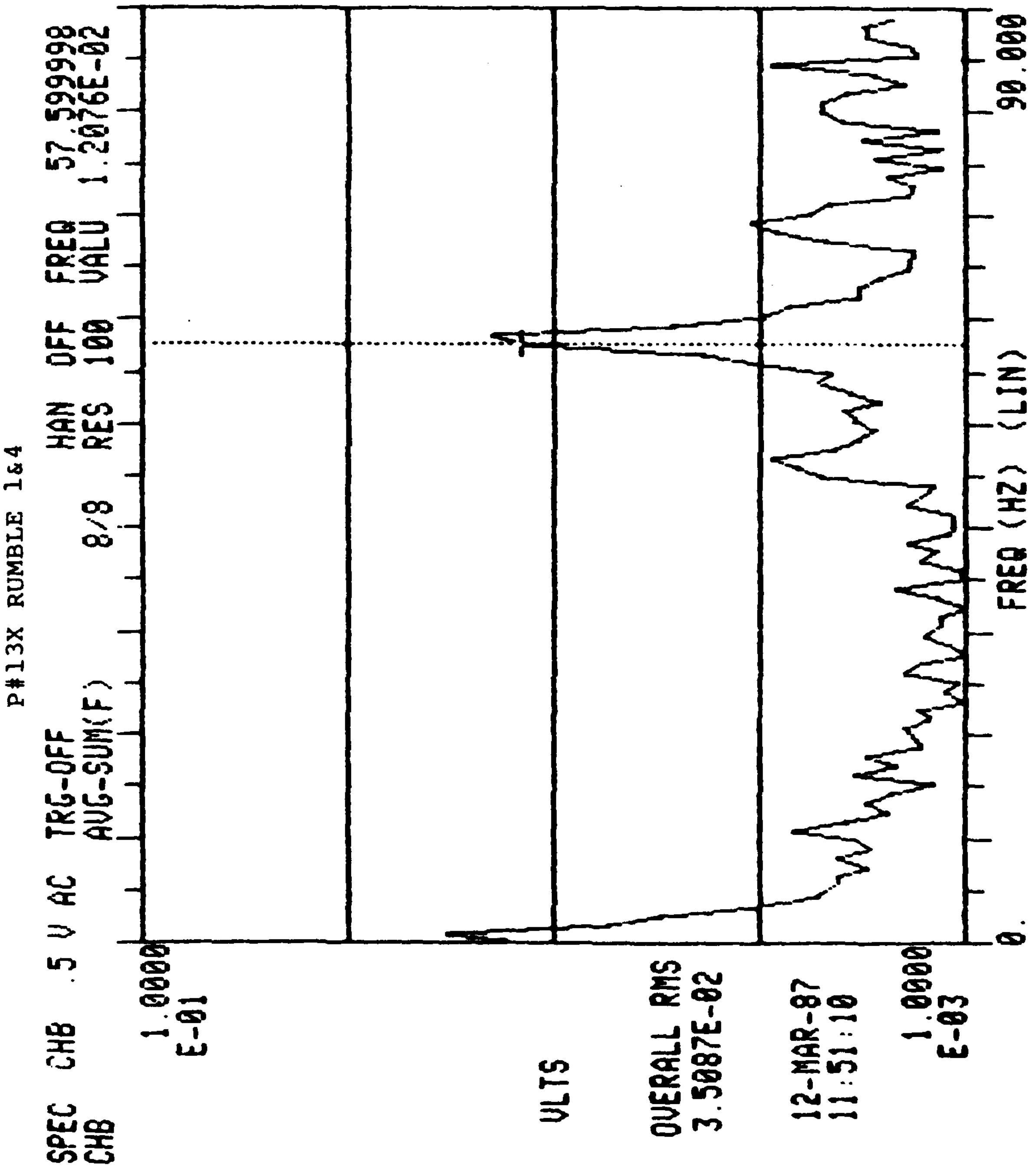




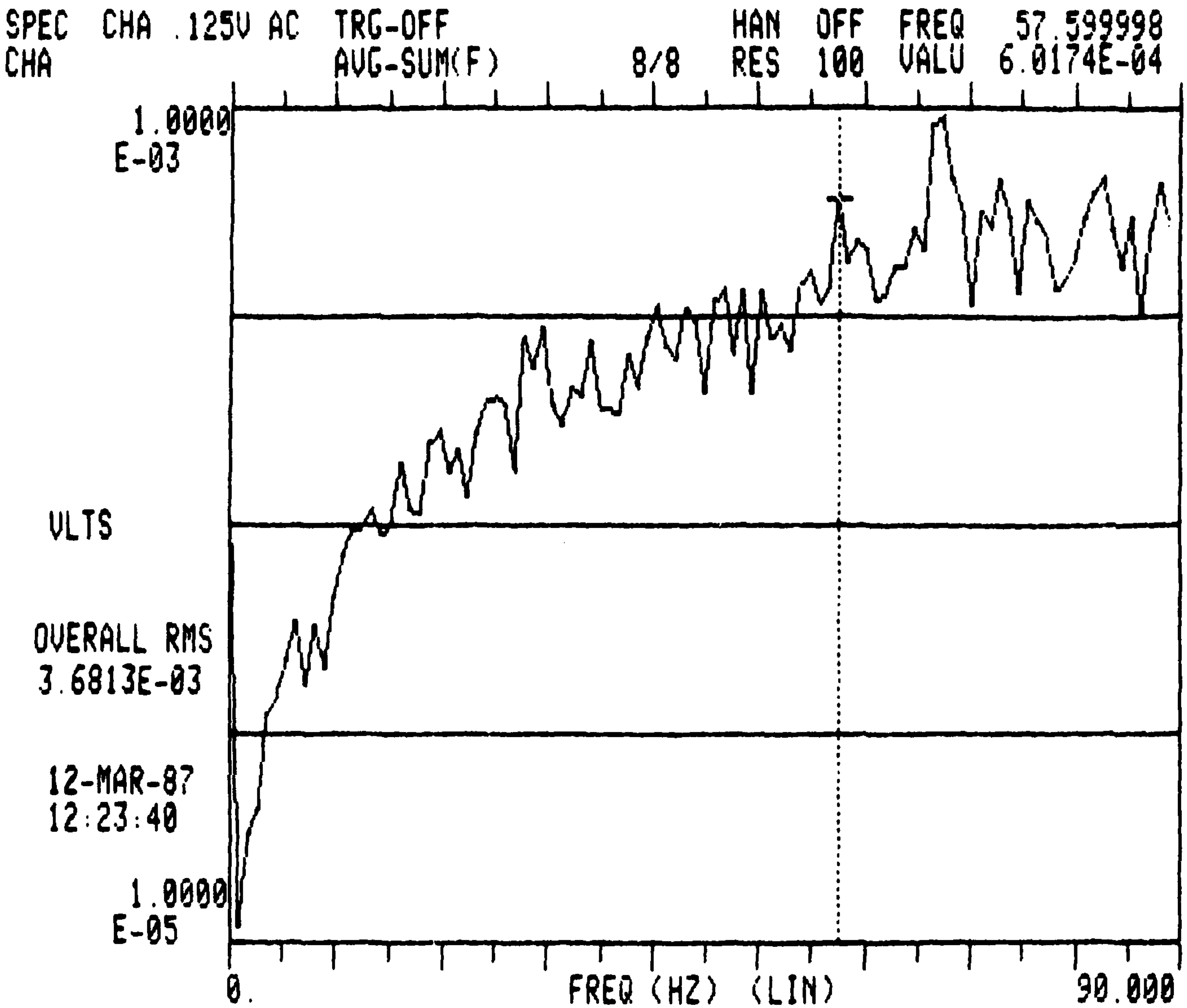
P#2X RUMBLE 1&4
SPEC CHA 2 V AC TRG-OFF HAN OFF FREQ 57.599998
CHA AVG-SUM(F) 8/8 RES 100 VALU 2.5632E-03
1.0000
E-02
VLTS
OVERALL RMS
1.8961E-02
12-MAR-87
11:48:00
1.0000
E-04
0
FREQ (HZ) (LIN)
90.000

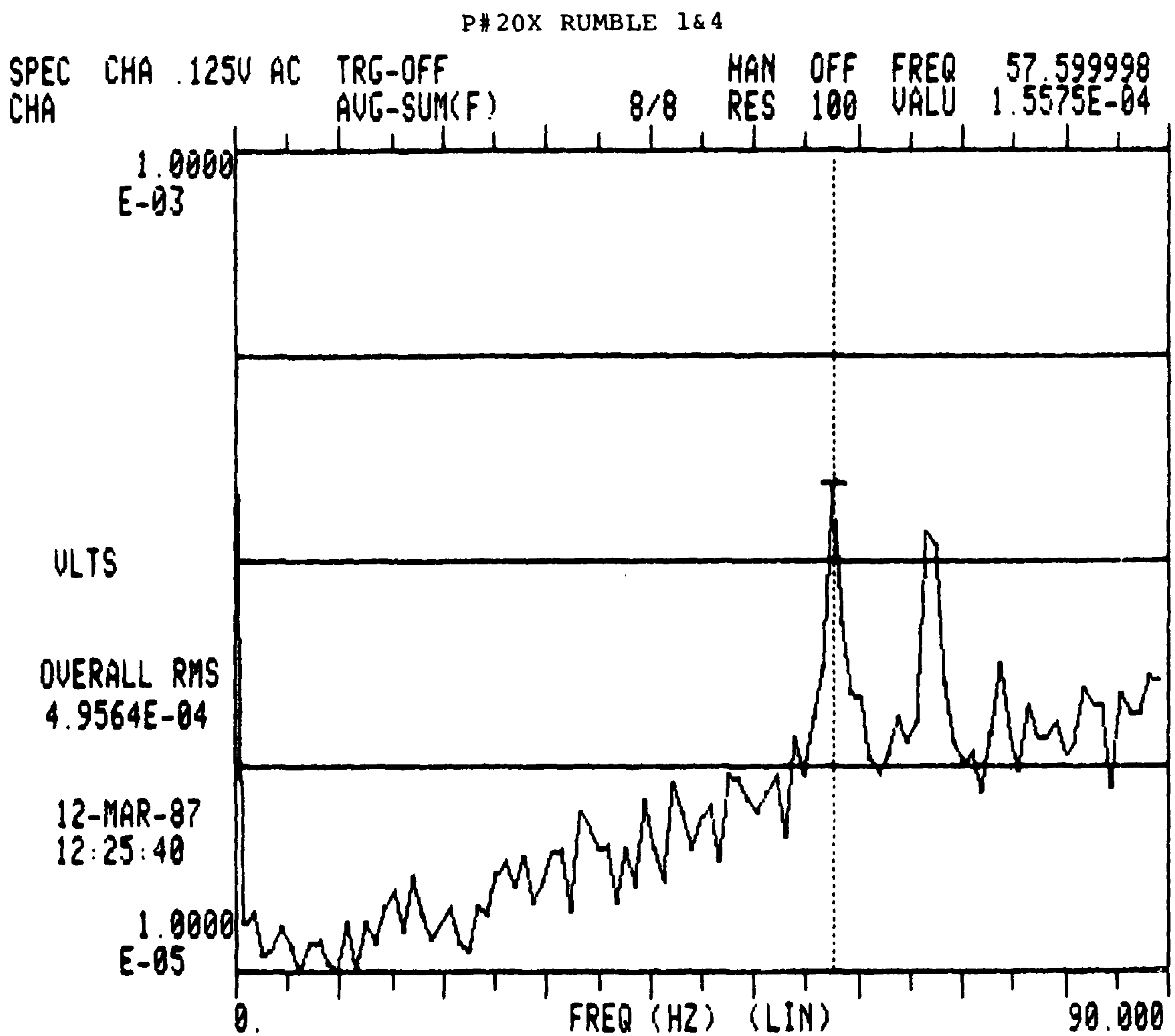
P#12X RUMBLE 1&4



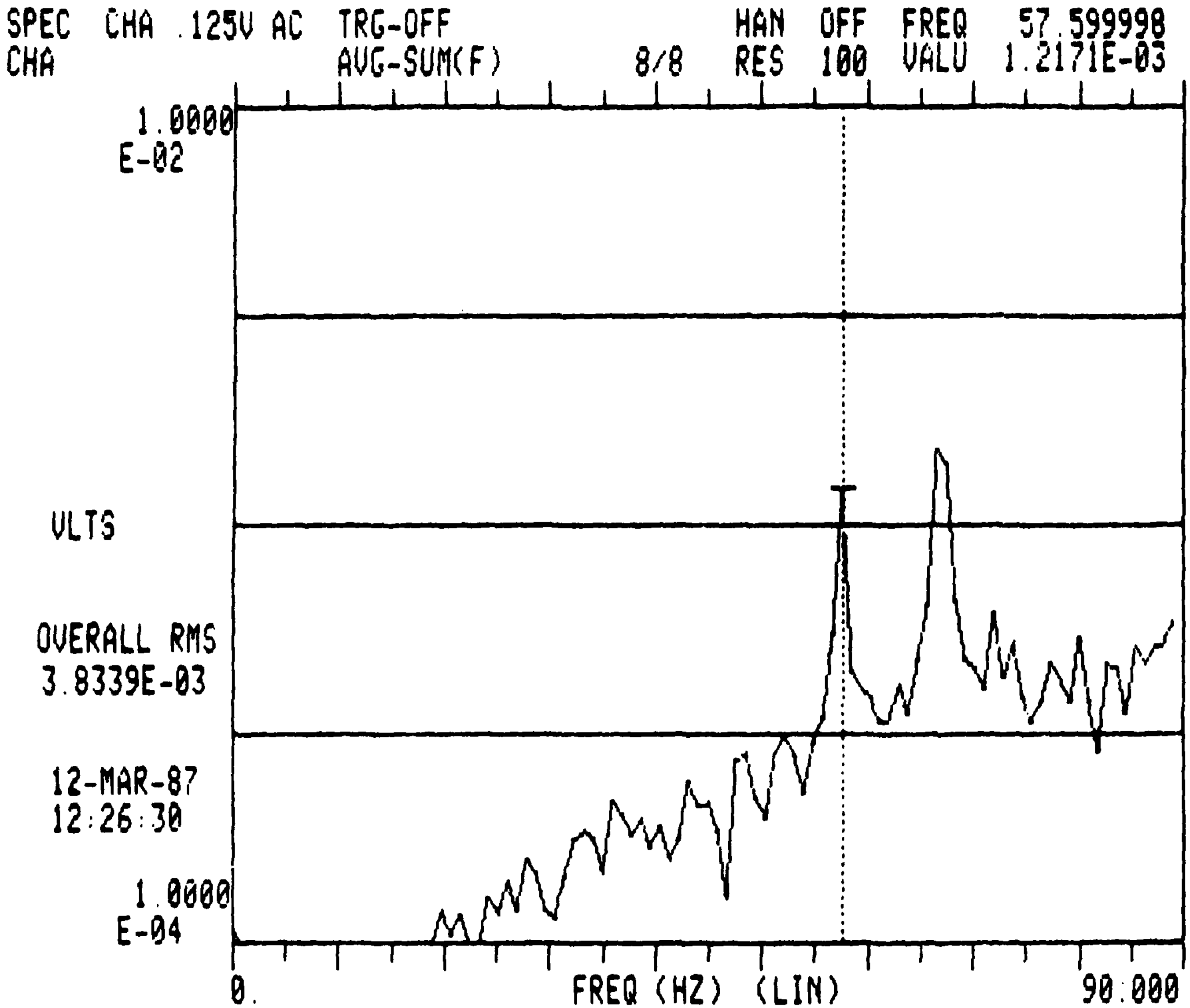

P#13X RUMBLE 1&4
SPEC CHB .5 V AC TRG-OFF AVG-SUM(F) 8/8 HAN RES OFF 100 FREQ VALU 57.599998 1.2076E-02
1.0000 E-01
VLTS
OVERALL RMS 3.5087E-02
12-MAR-87 11:51:10
1.0000 E-03
0.
90.000
FREQ (HZ) (LIN)

P#17X RUMBLE 1&4

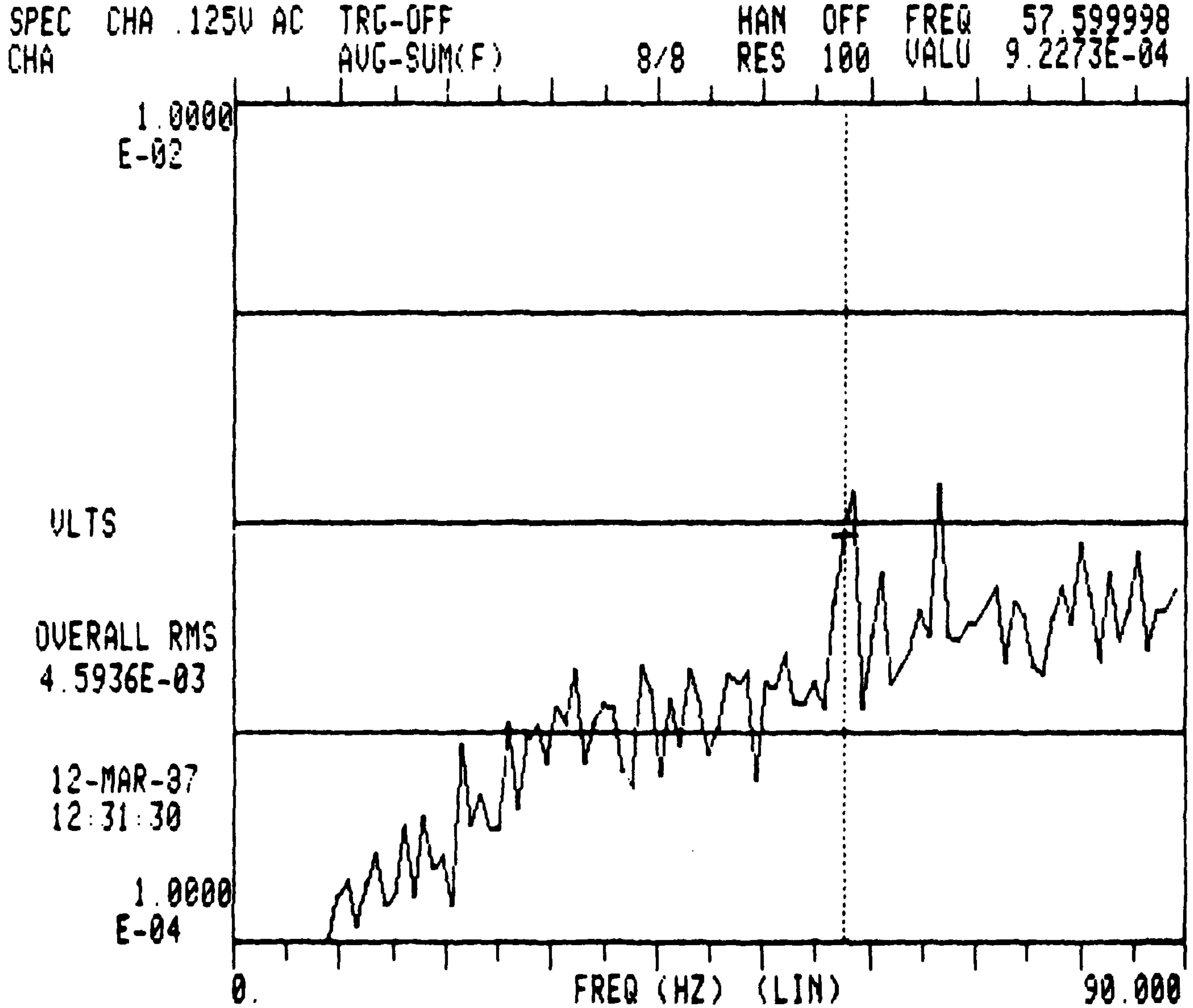


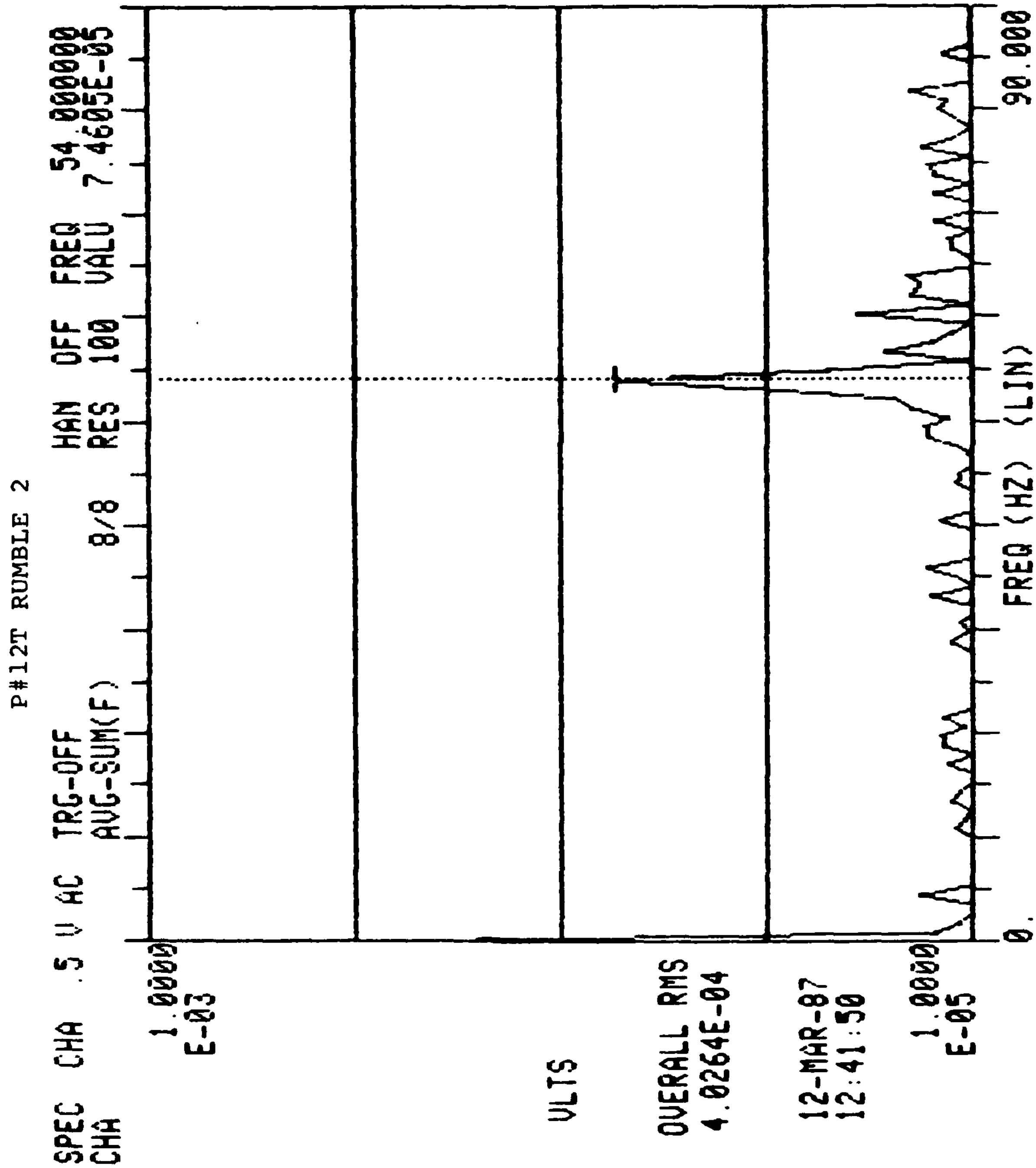

P#20X RUMBLE 1&4
SPEC CHA .125V AC TRG-OFF HAN OFF FREQ 57.599998
CHA AVG-SUM(F) 8/8 RES 100 VALU 1.5575E-04
1.0000 E-03
VLTS
OVERALL RMS 4.9564E-04
12-MAR-87 12:25:40
1.0000 E-05
0.
FREQ (HZ) (LIN)
90.000

P#21X RUMBLE 1&4

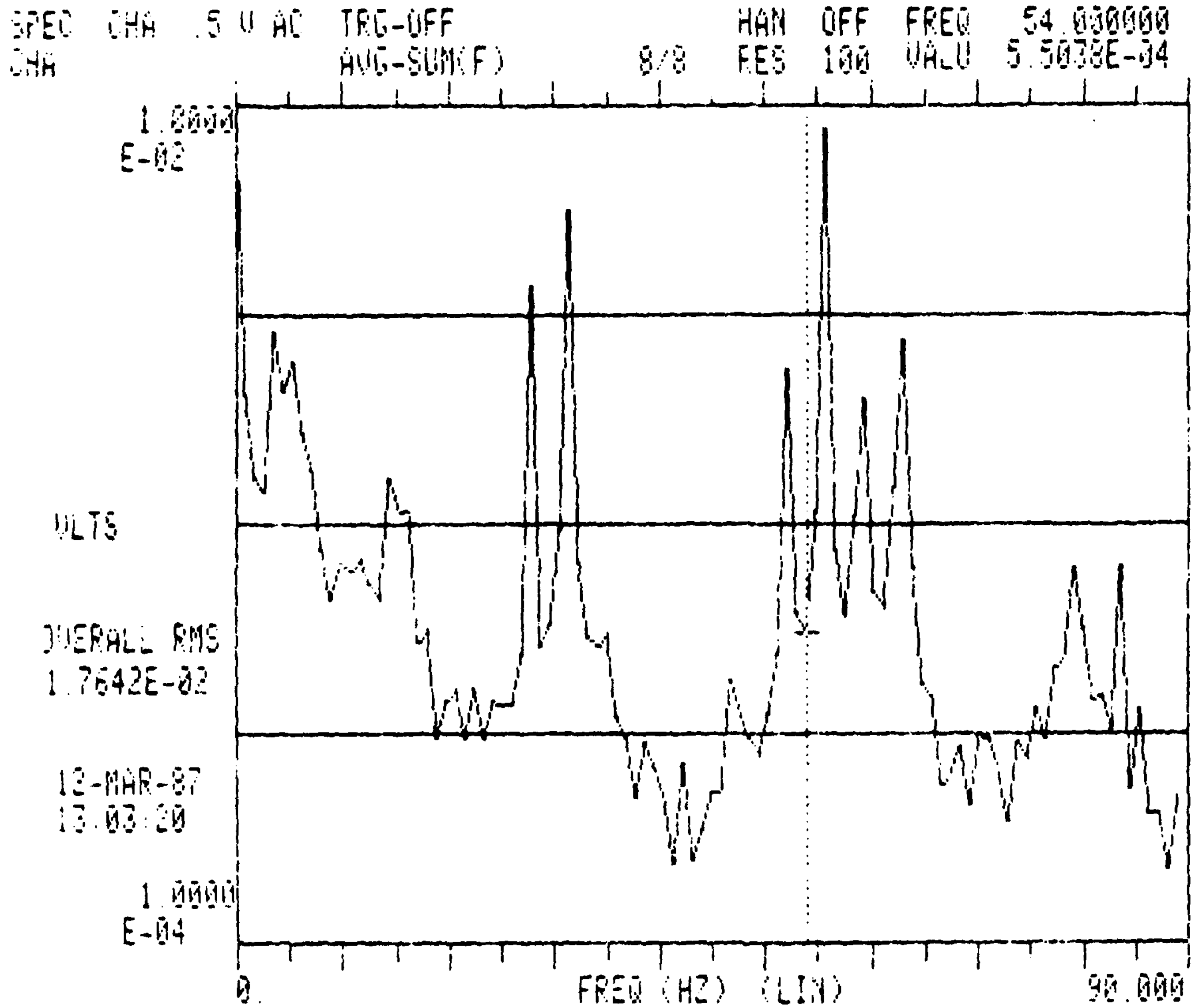


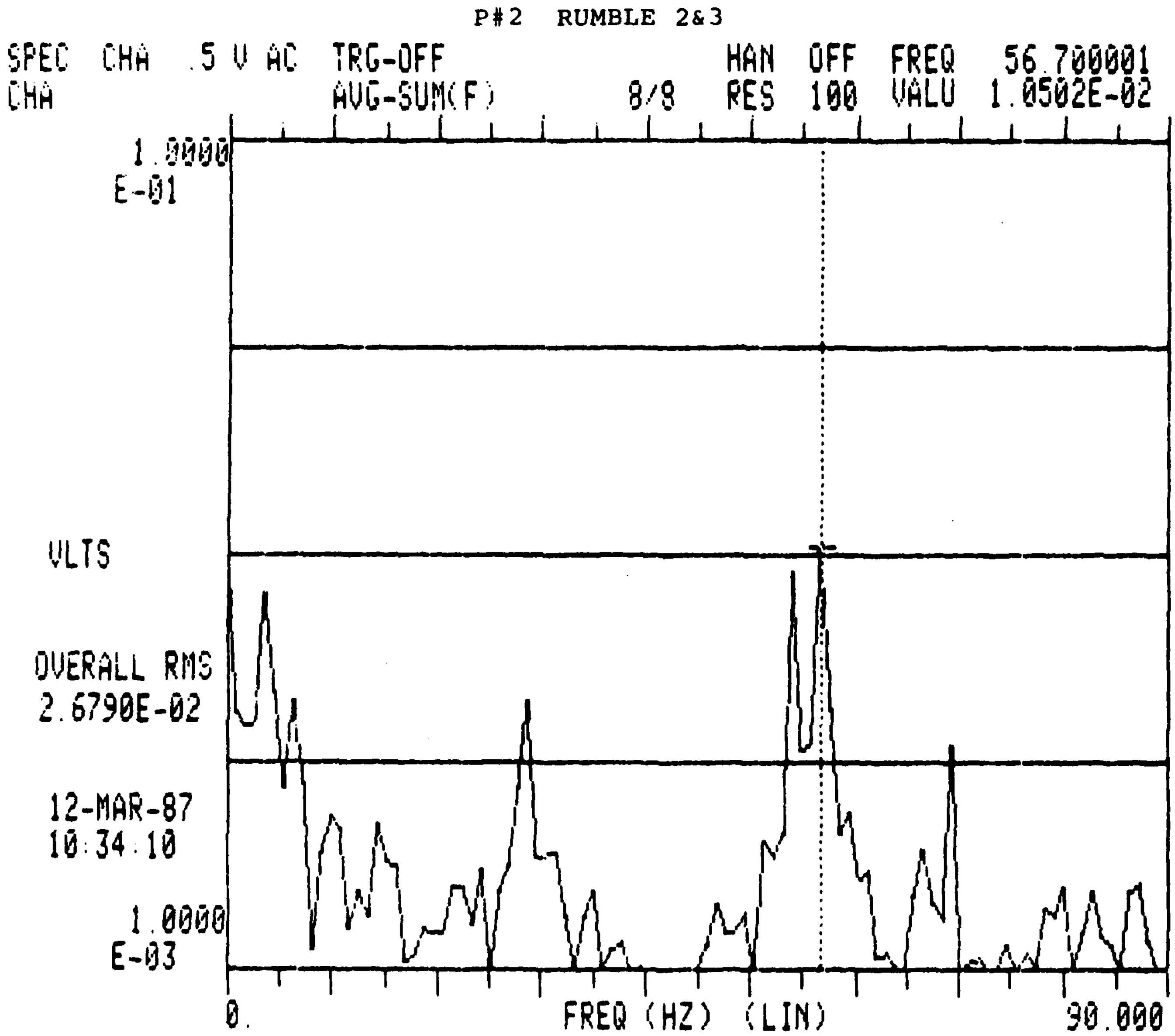
P#17Y RUMBLE 3



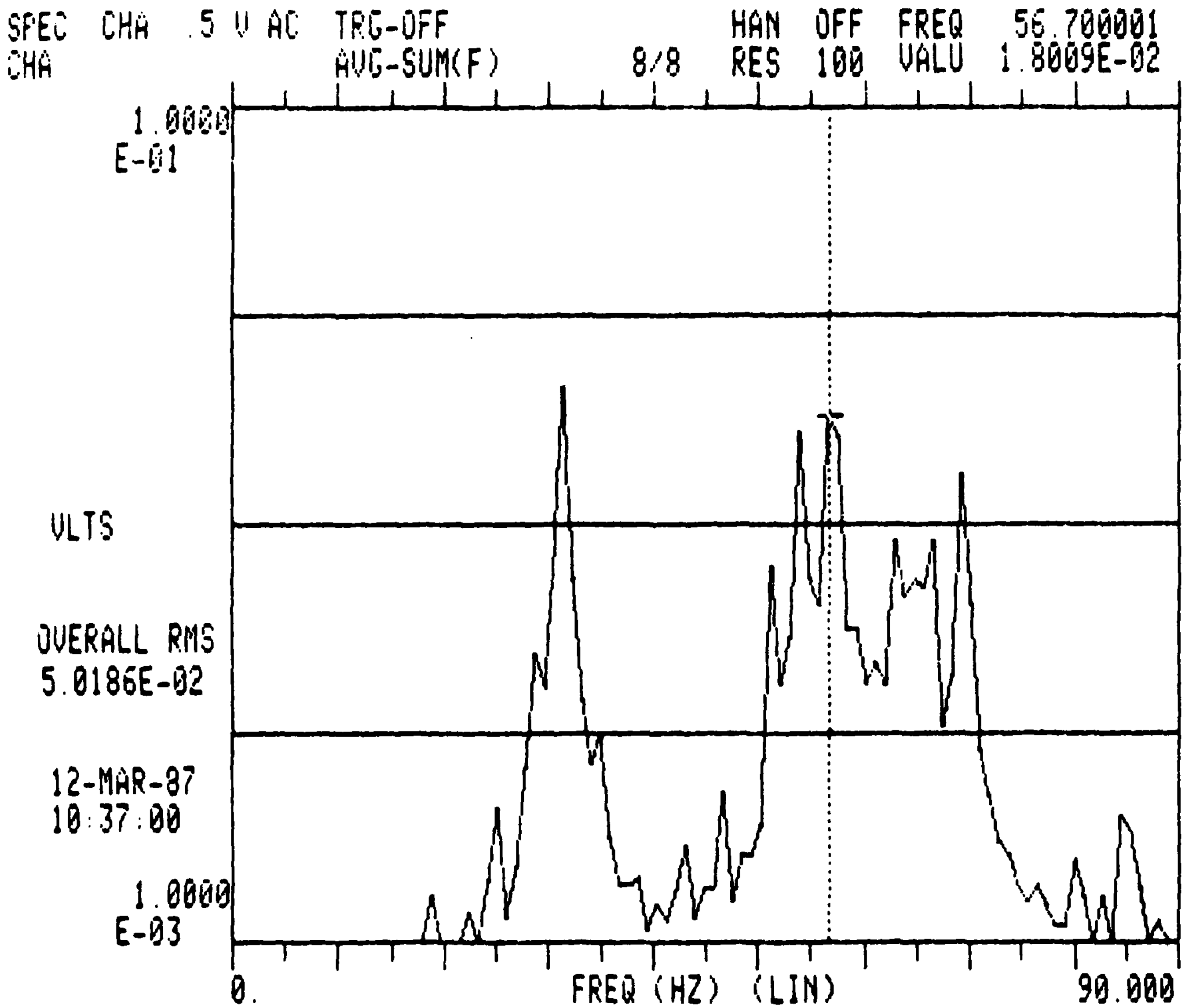

P#12T RUMBLE 2
SPEC CHA .5 V AC TRG-OFF 8/8 HAN OFF FREQ 54.000000
CHA AVG-SUM(F) RES 100 VALU 7.4605E-05
1.0000 E-03
VLTS
OVERALL RMS 4.0264E-04
12-MAR-87 12:41:50
1.0000 E-05
0.
90.000
FREQ (HZ) (LIN)

P#14S RUMBLE 2



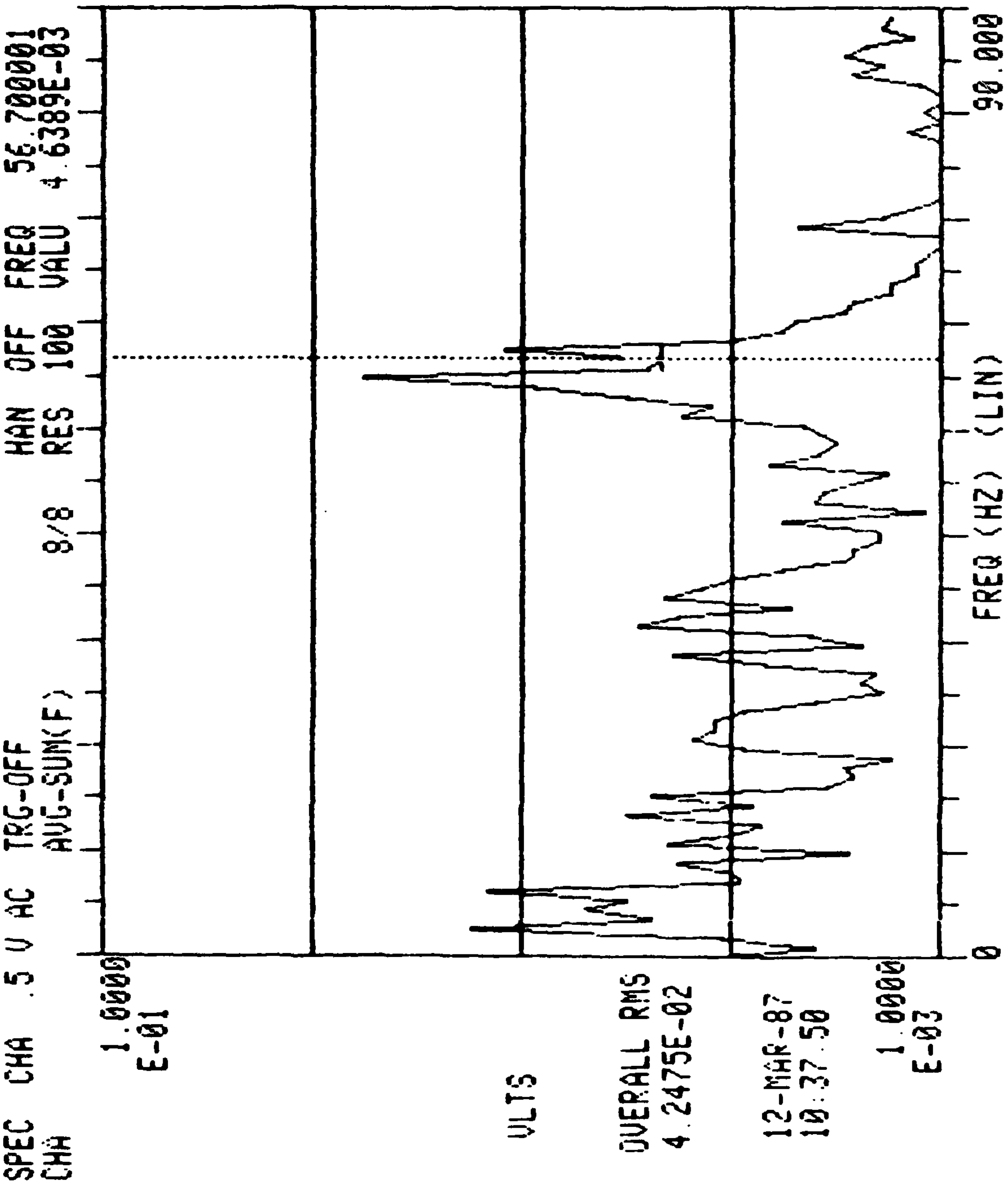

P#2 RUMBLE 2&3
SPEC CHA .5 V AC TRG-OFF HAN OFF FREQ 56.700001
CHA AVG-SUM(F) 8/8 RES 100 VALU 1.0502E-02
1.0000
E-01
VLTS
OVERALL RMS
2.6790E-02
12-MAR-87
10:34:10
1.0000
E-03
0.
FREQ (HZ) (LIN)
90.000

P#3 RUMBLE 2&3



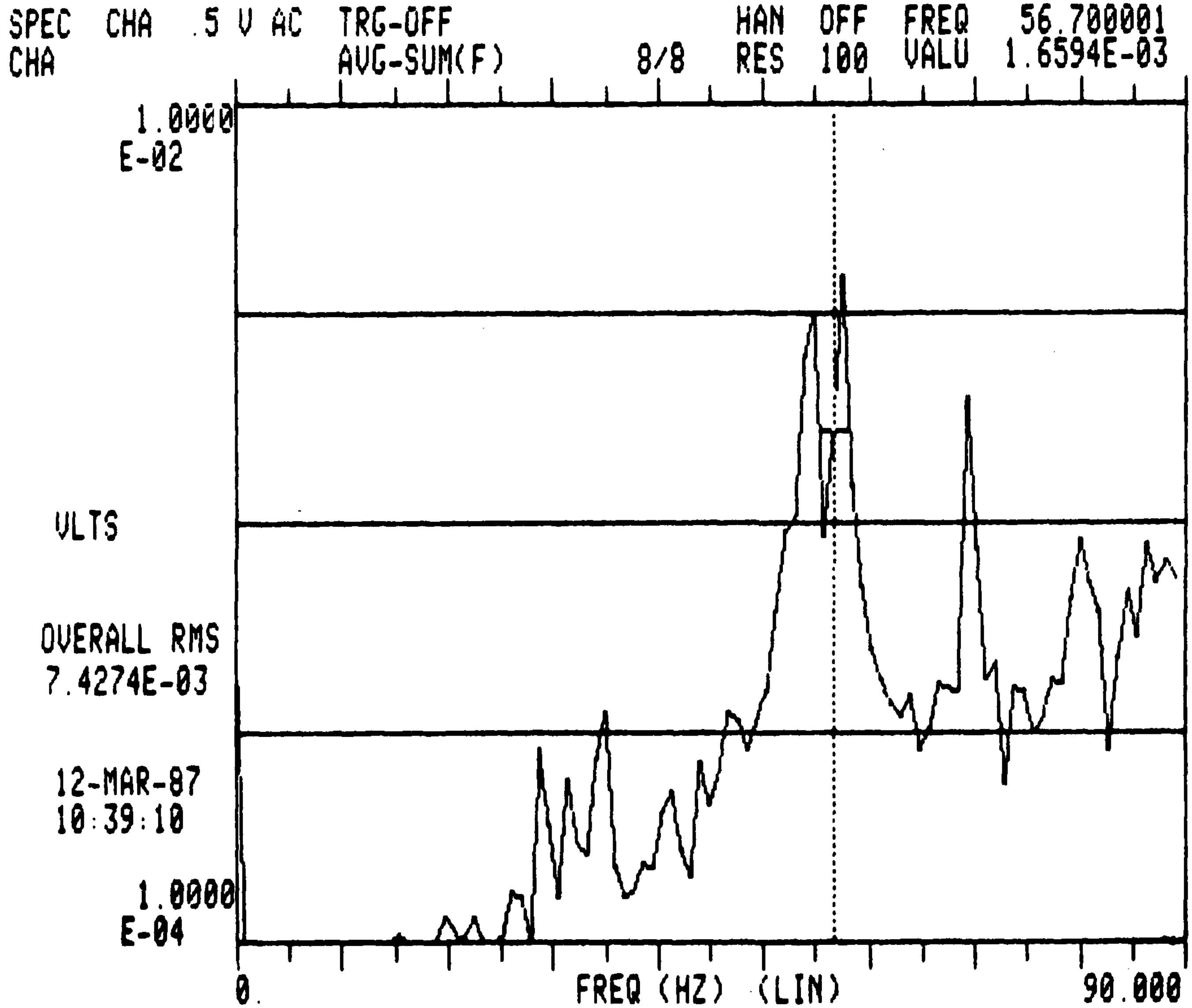
SPEC CHA .5 V AC TRG-OFF HAN OFF FREQ 56.700001
CHA AVG-SUM(F) 8/8 RES 100 VALU 1.8009E-02
1.0000
E-01
VLTS
OVERALL RMS
5.0186E-02
12-MAR-87
10:37:00
1.0000
E-03
0.
FREQ (HZ) (LIN)
90.000

P#4 RUMBLE 2&3



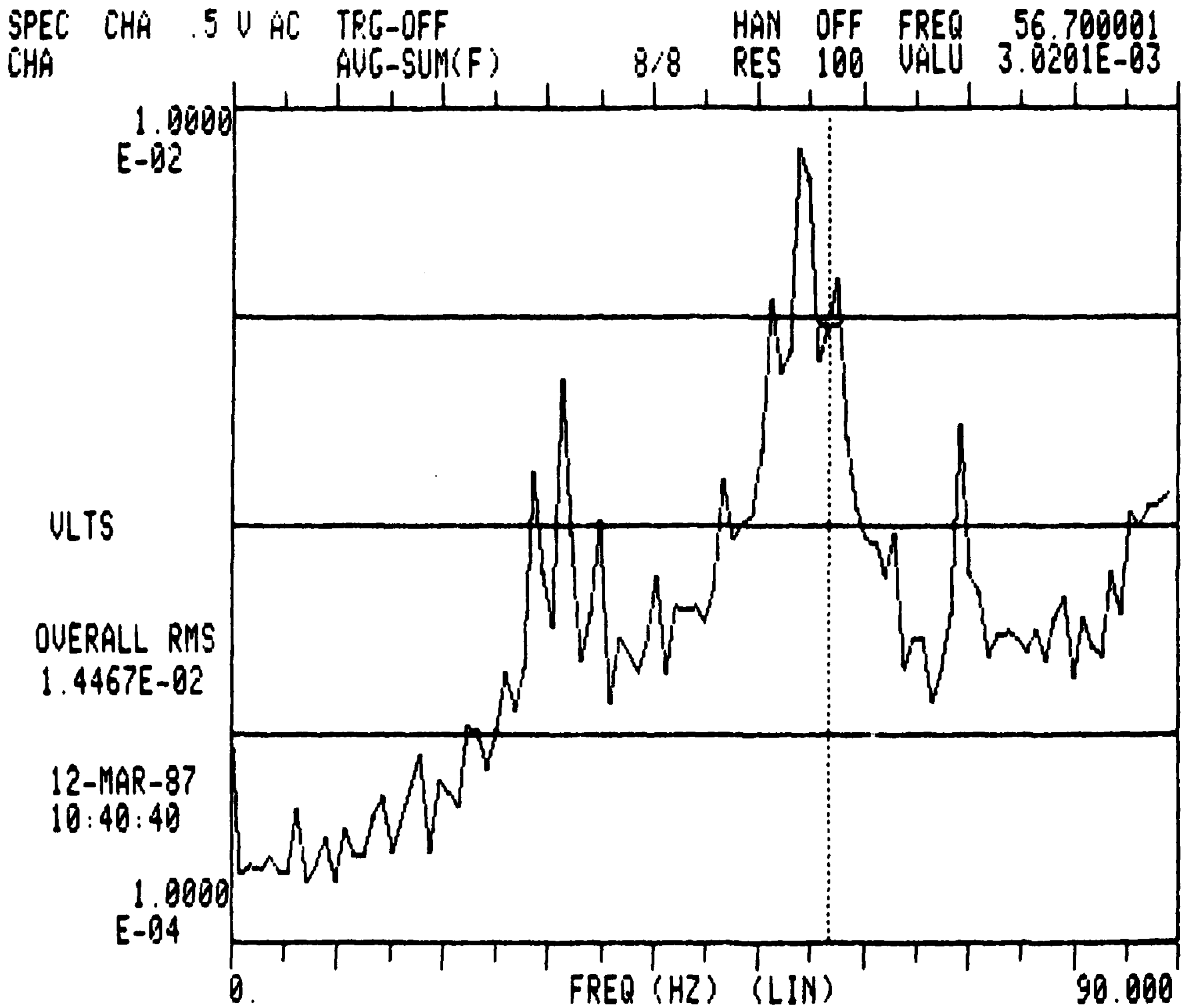
SPEC CHA
CHA .5 V AC
TRG-OFF
AVG-SUM(F)
8/8
HAN
RES
OFF
100
FREQ
VALU
56.700001
4.6389E-03
1.0000
E-01
VLTS
OVERALL RMS
4.2475E-02
12-MAR-87
10:37:50
1.0000
E-03
0
FREQ (HZ) (LIN)
90.000

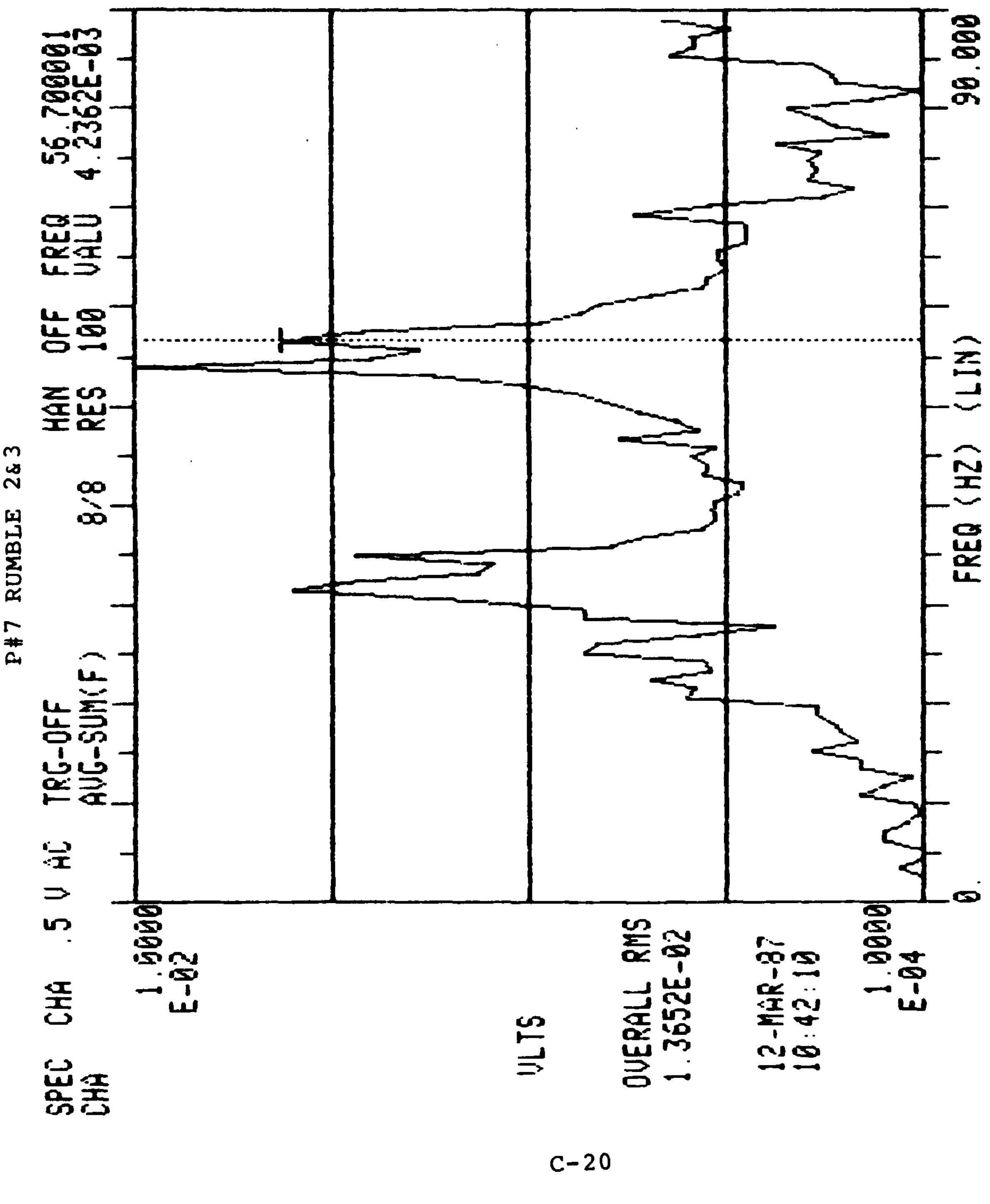
P#5 RUMBLE 2&3

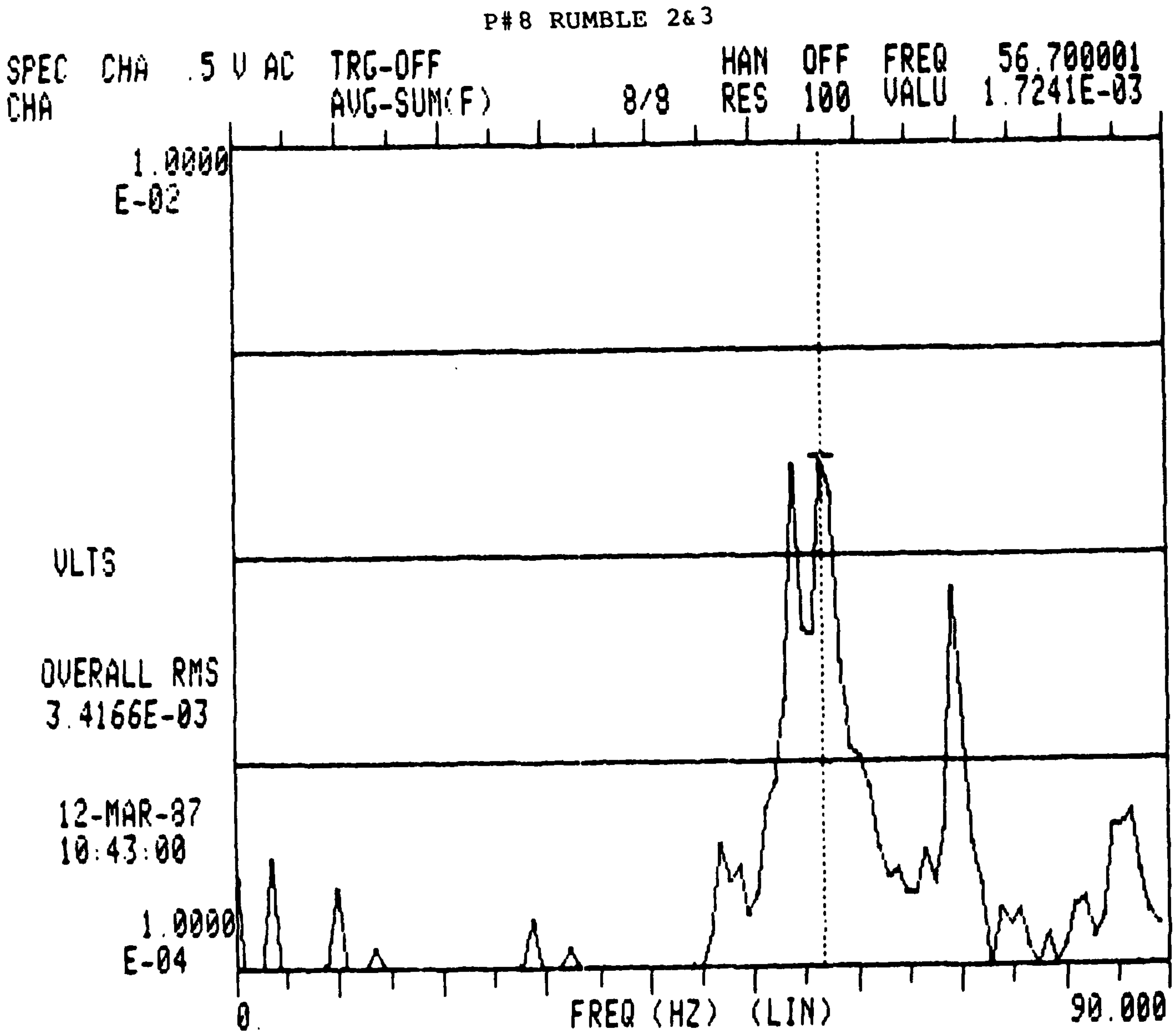


SPEC CHA .5 V AC TRG-OFF HAN OFF FREQ 56.700001
CHA AVG-SUM(F) 8/8 RES 100 VALU 1.6594E-03
1.0000 E-02
VLTS
OVERALL RMS 7.4274E-03
12-MAR-87 10:39:10
1.0000 E-04
0.
FREQ (HZ) (LIN)
90.000

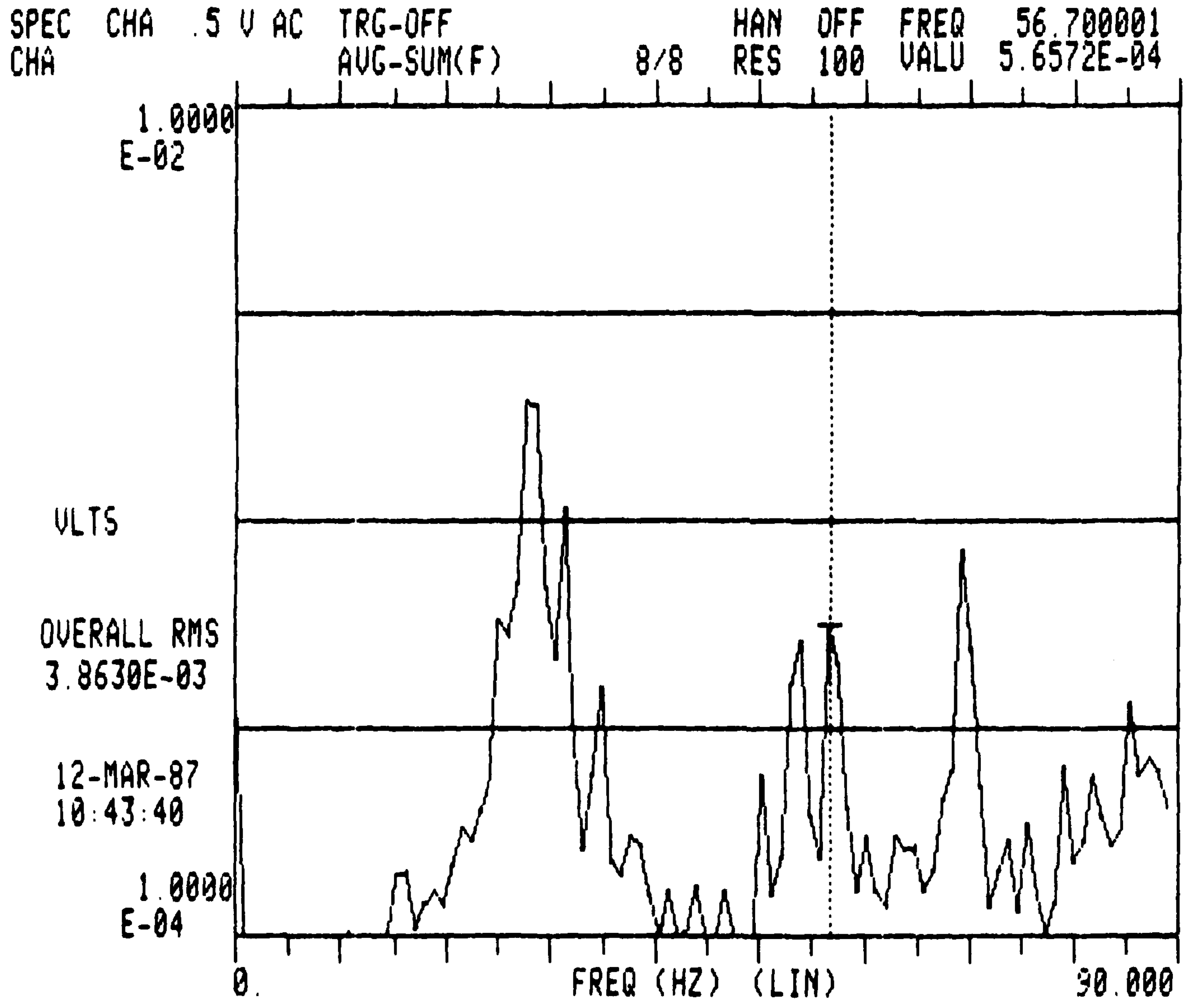
P#6 RUMBLE 2&3


SPEC CHA .5 V AC TRG-OFF HAN OFF FREQ 56.700001
CHA AVG-SUM(F) 8/8 RES 100 VALU 3.0201E-03
1.0000
E-02
VLTS
OVERALL RMS
1.4467E-02
12-MAR-87
10:40:40
1.0000
E-04
0.
FREQ (HZ) (LIN)
90.000

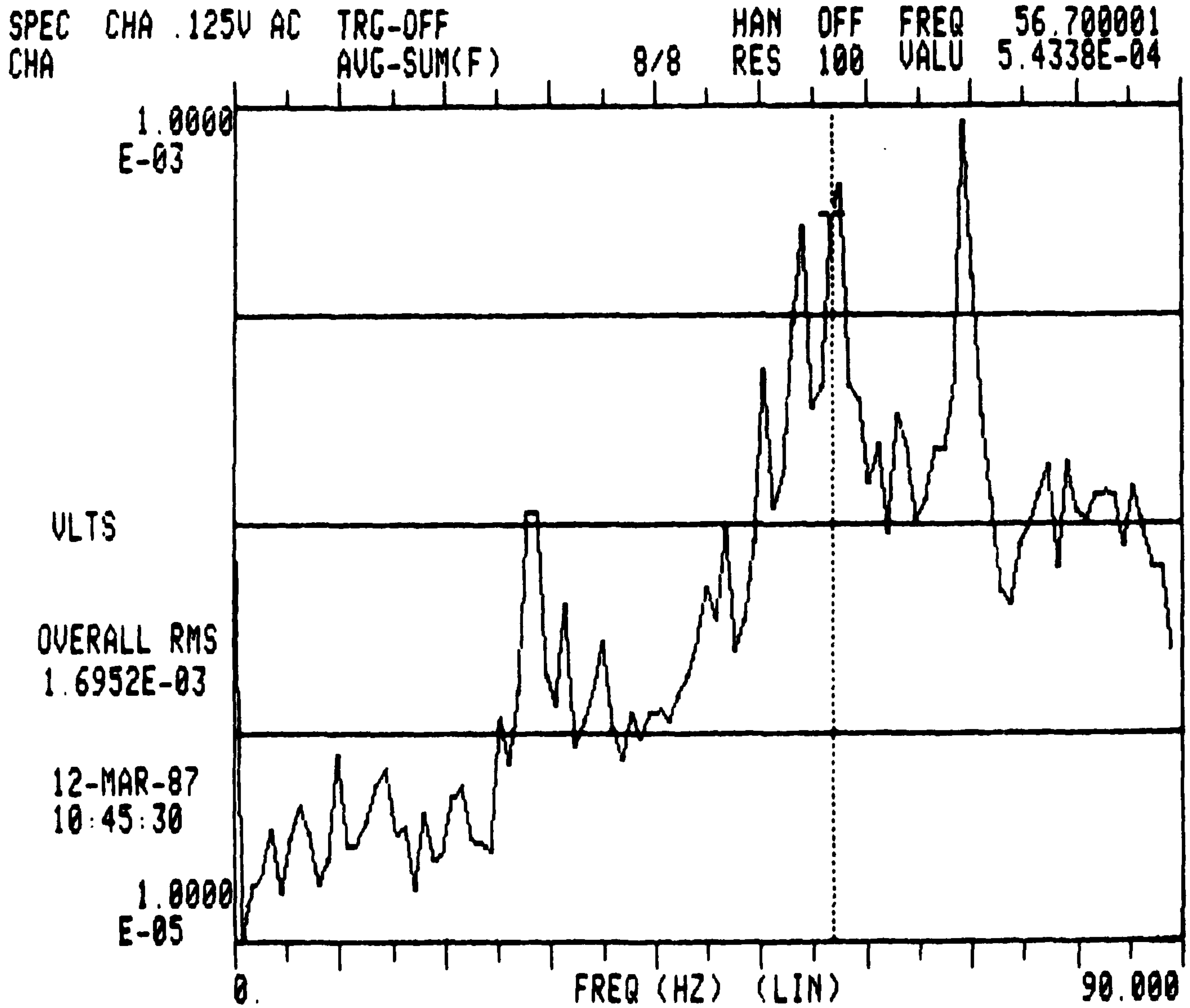

P#7 RUMBLE 2&3
SPEC CHA .5 V AC TRG-OFF HAN OFF FREQ 56.700001
CHA AVG-SUM(F) 8/8 RES 100 VALU 4.2362E-03
1.0000
E-02
VLTS
OVERALL RMS
1.3652E-02
12-MAR-87
10:42:10
1.0000
E-04
0.
90.000
FREQ (HZ) (LIN)


P#8 RUMBLE 2&3
SPEC CHA .5 V AC TRG-OFF HAN OFF FREQ 56.700001
CHA AVG-SUM(F) 8/8 RES 100 VALU 1.7241E-03
1.0000 E-02
VLTS
OVERALL RMS 3.4166E-03
12-MAR-87 10:43:00
1.0000 E-04
0
FREQ (HZ) (LIN)
90.000

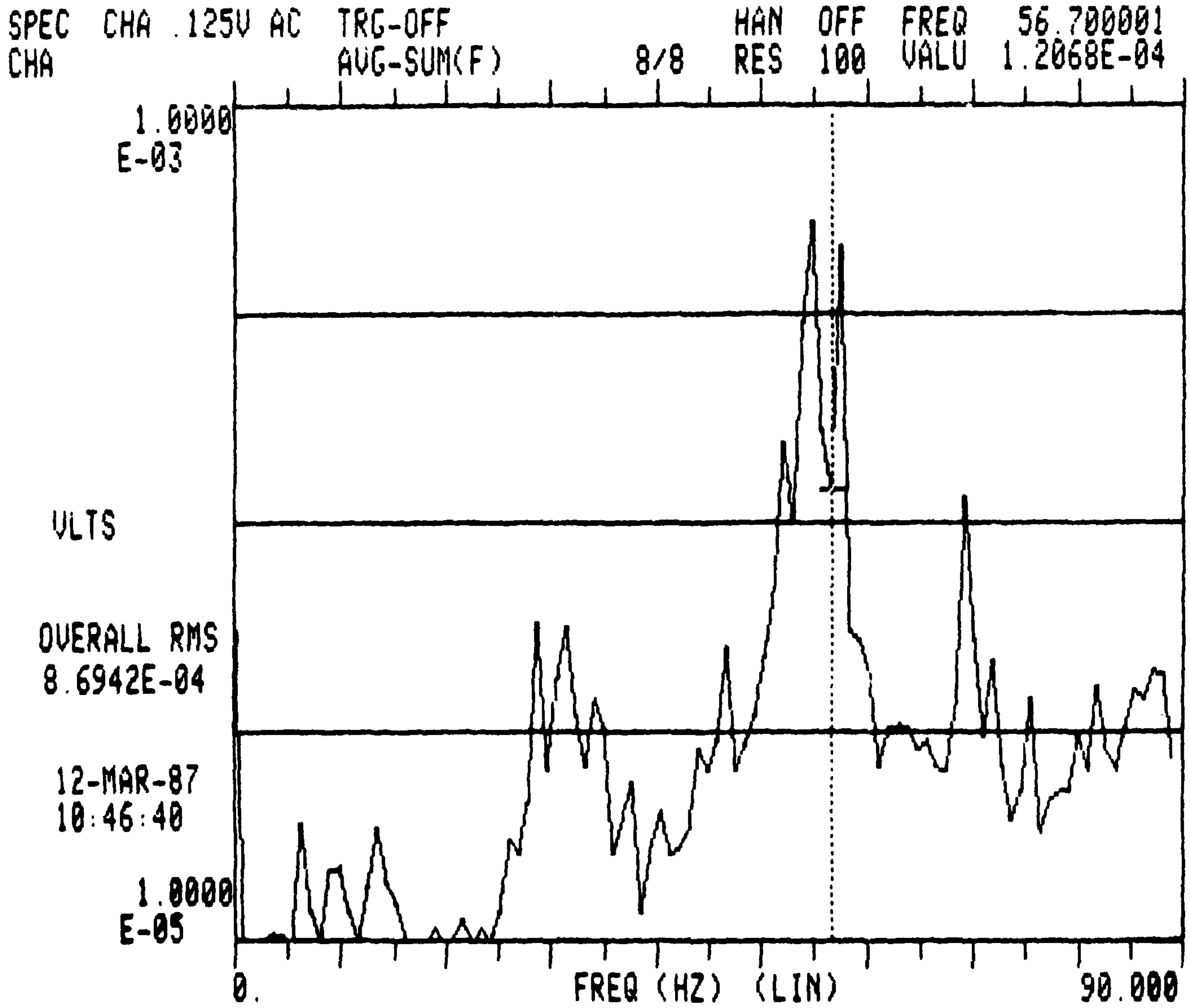
P#9 RUMBLE 2&3

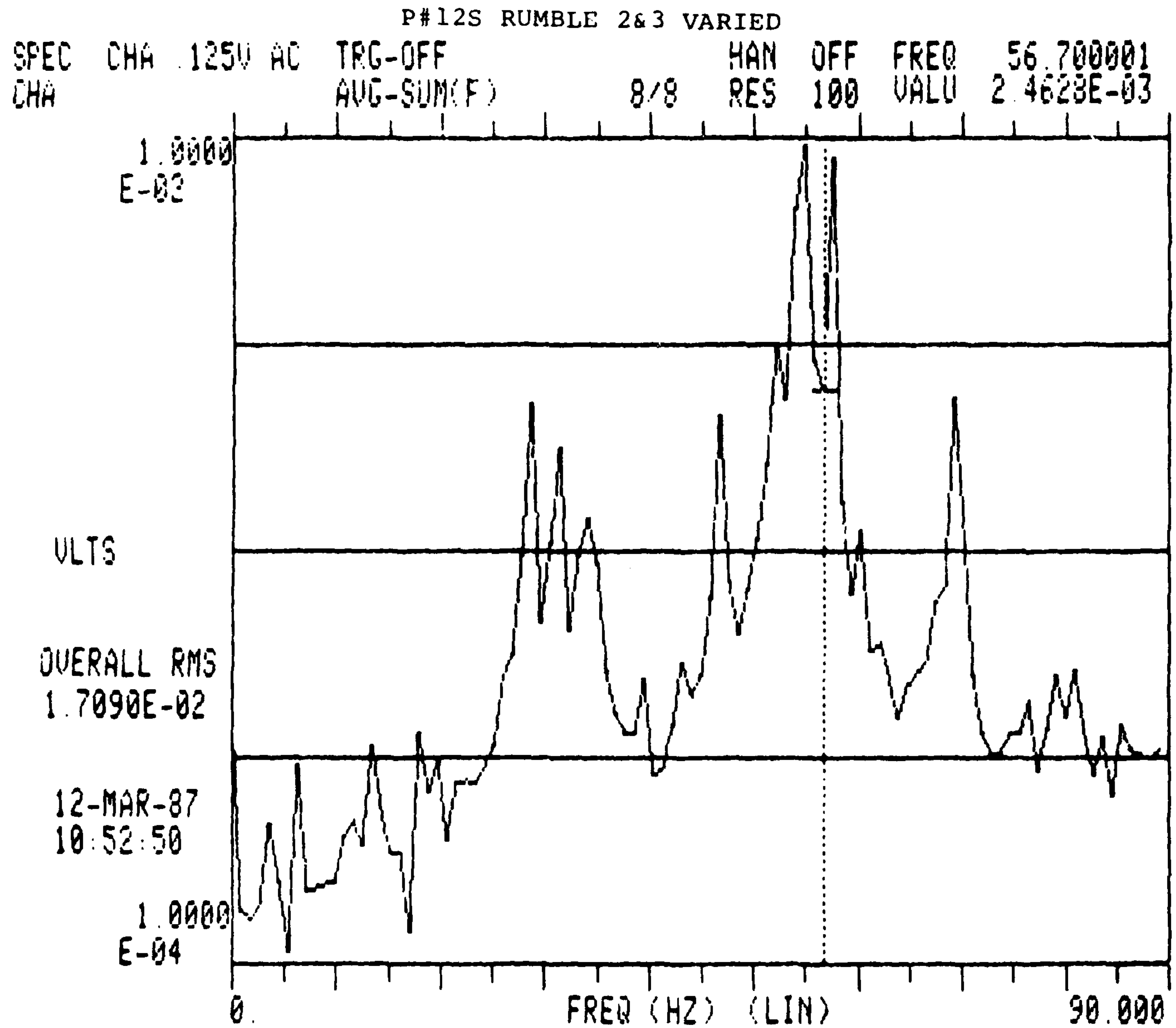

SPEC CHA .5 V AC TRG-OFF HAN OFF FREQ 56.700001
CHA AVG-SUM(F) 8/8 RES 100 VALU 5.6572E-04
1.0000
E-02
VLTS
OVERALL RMS
3.8630E-03
12-MAR-87
10:43:40
1.0000
E-04
0.
FREQ (HZ) (LIN)
90.000

P#10 RUMBLE 2&3

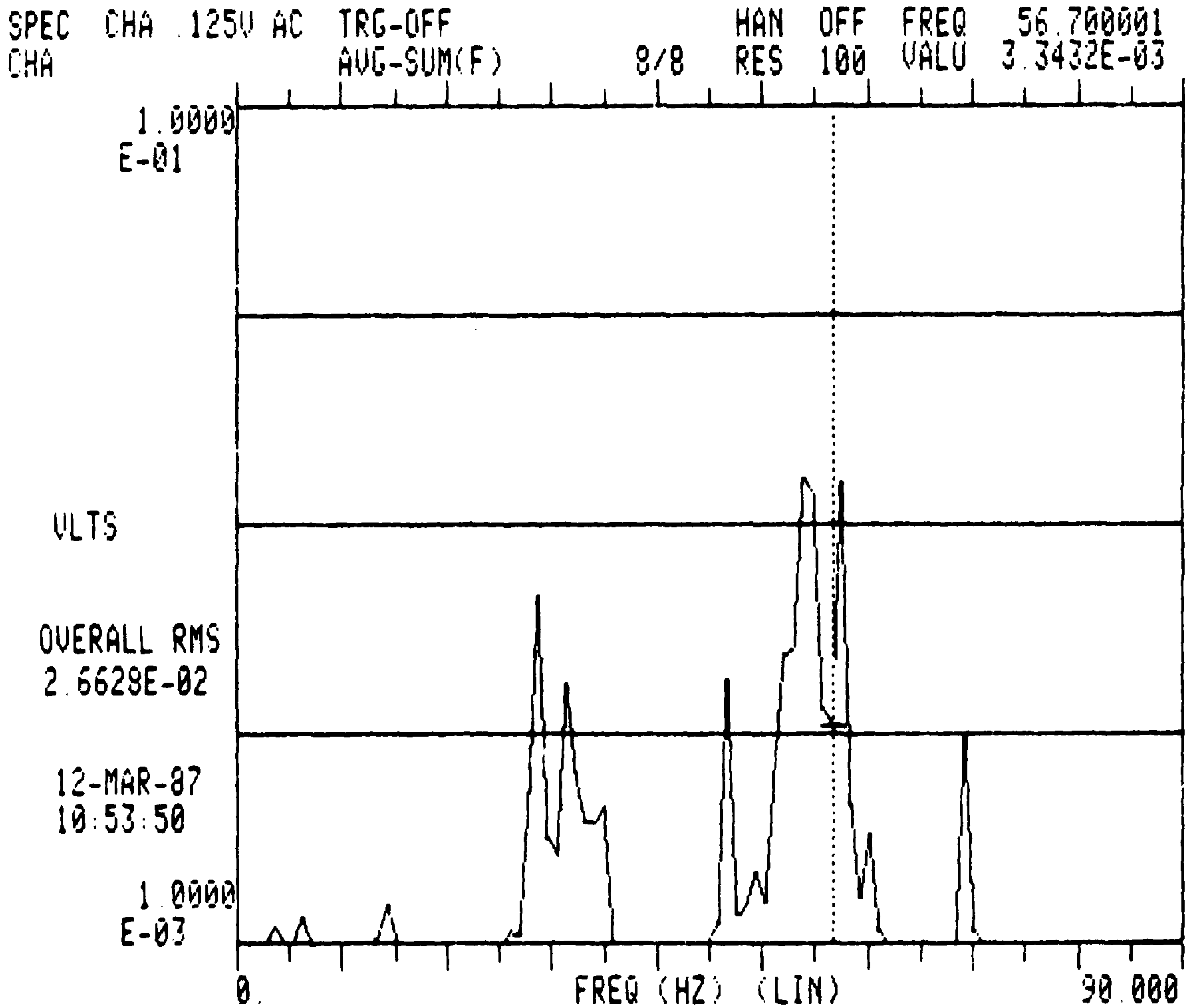


P#11 RUMBLE 2&3

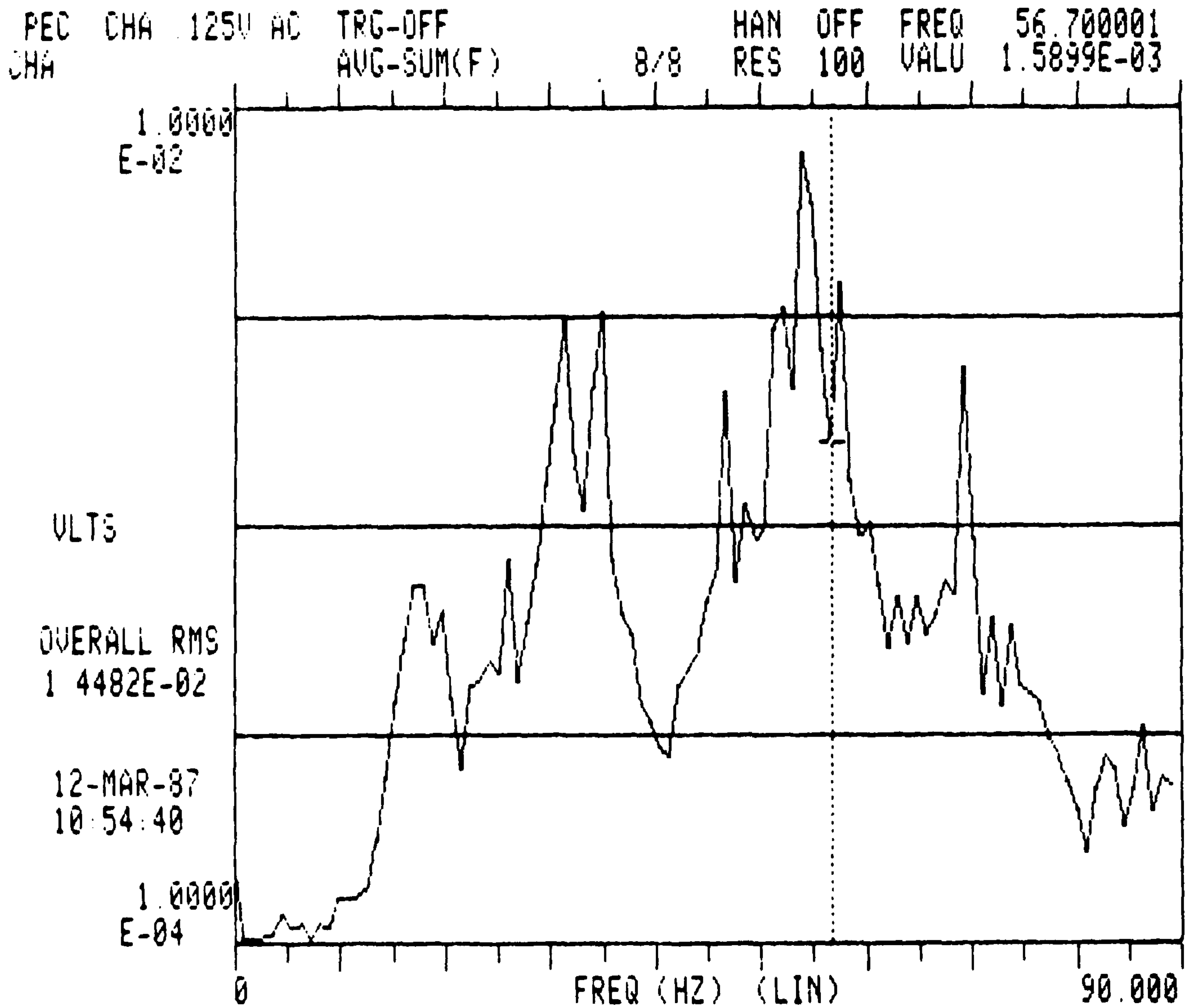



P#12S RUMBLE 2&3 VARIED
SPEC CHA .125V AC TRG-OFF HAN OFF FREQ 56.700001
CHA AVG-SUM(F) 8/8 RES 100 VALU 2.4623E-03
1.0000
E-03
VLTS
OVERALL RMS
1.7090E-02
12-MAR-87
10:52:50
1.0000
E-04
0.
FREQ (HZ) (LIN)
90.000

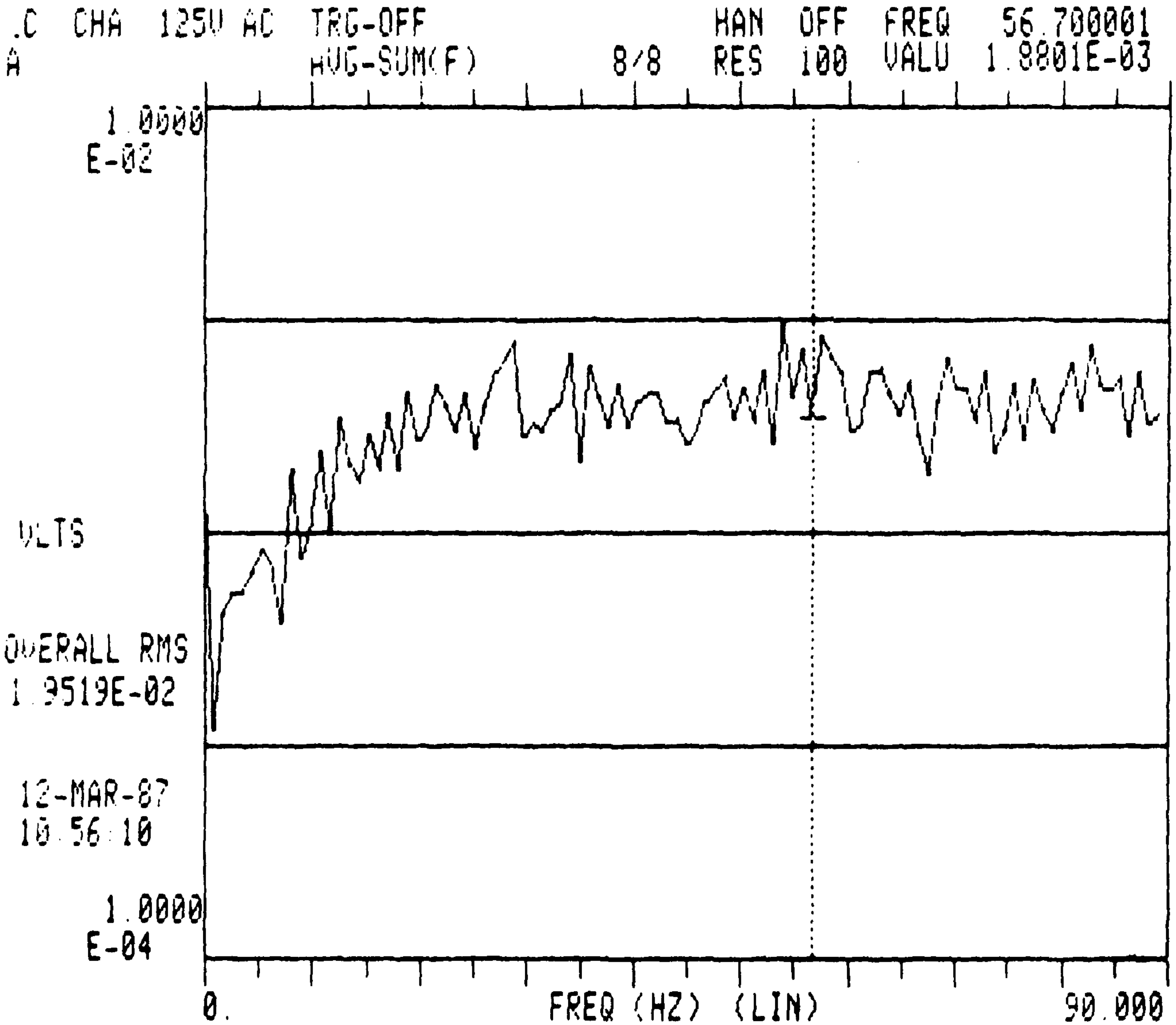
P#12 RUMBLE 2&3



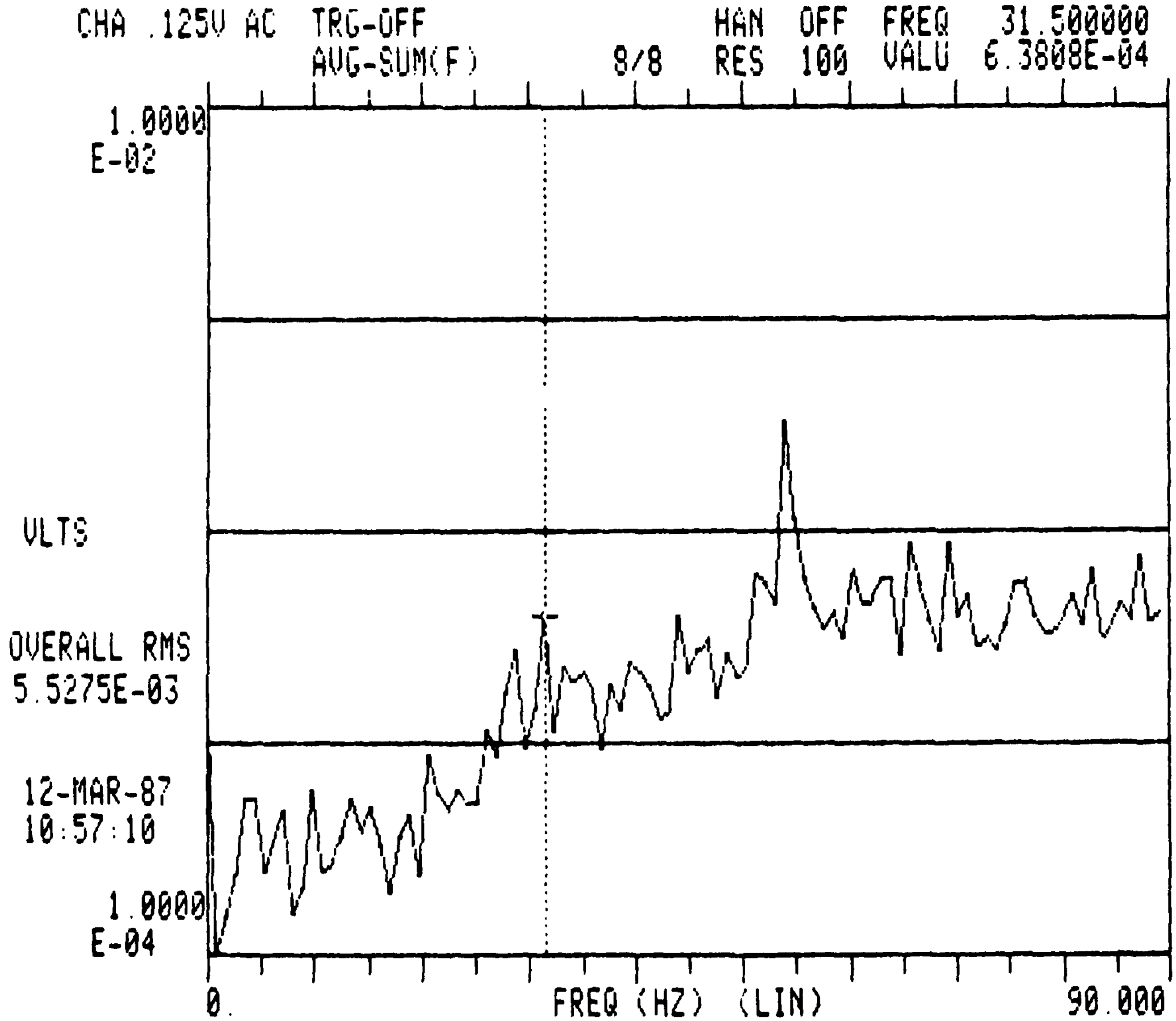
P#13 RUMBLE 2&3

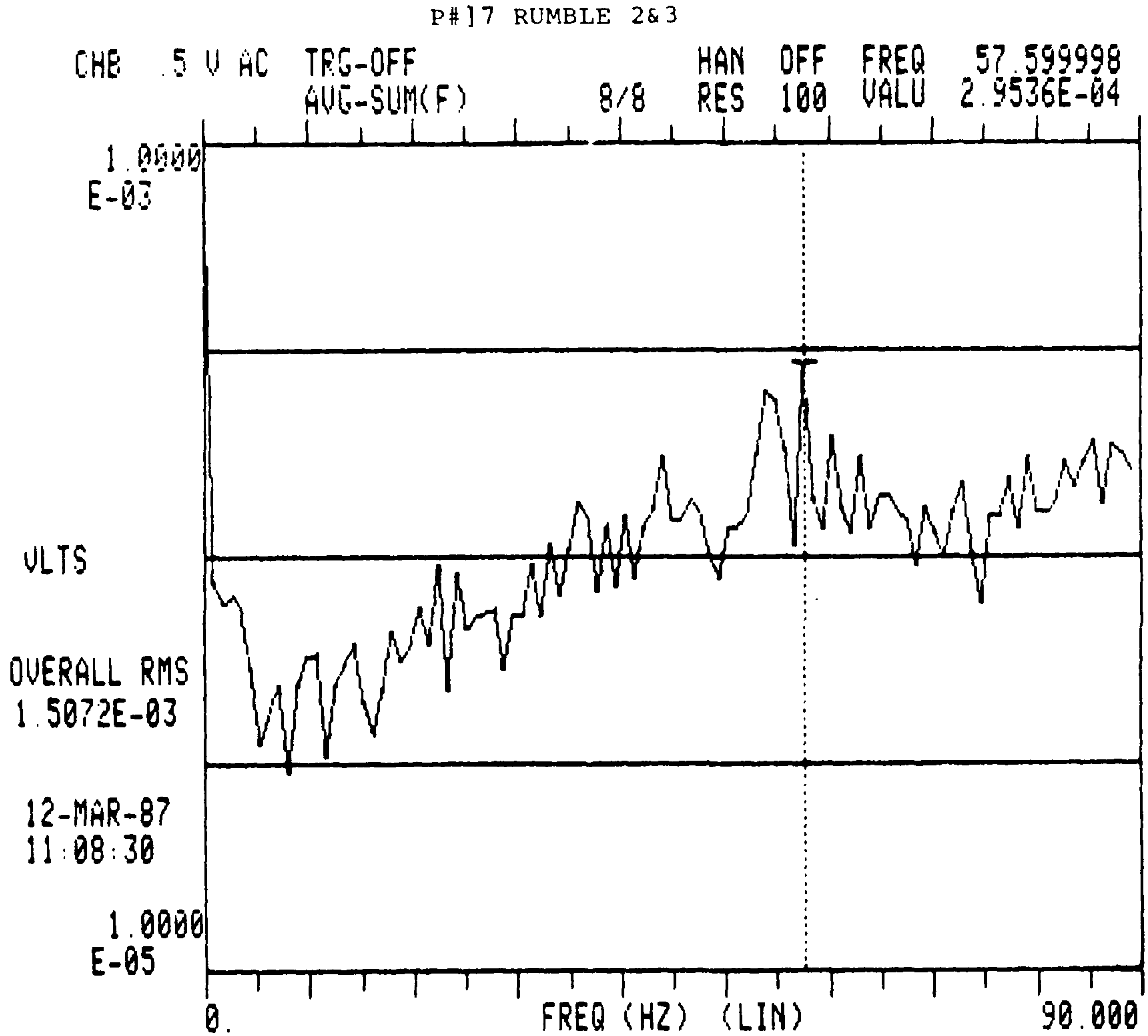


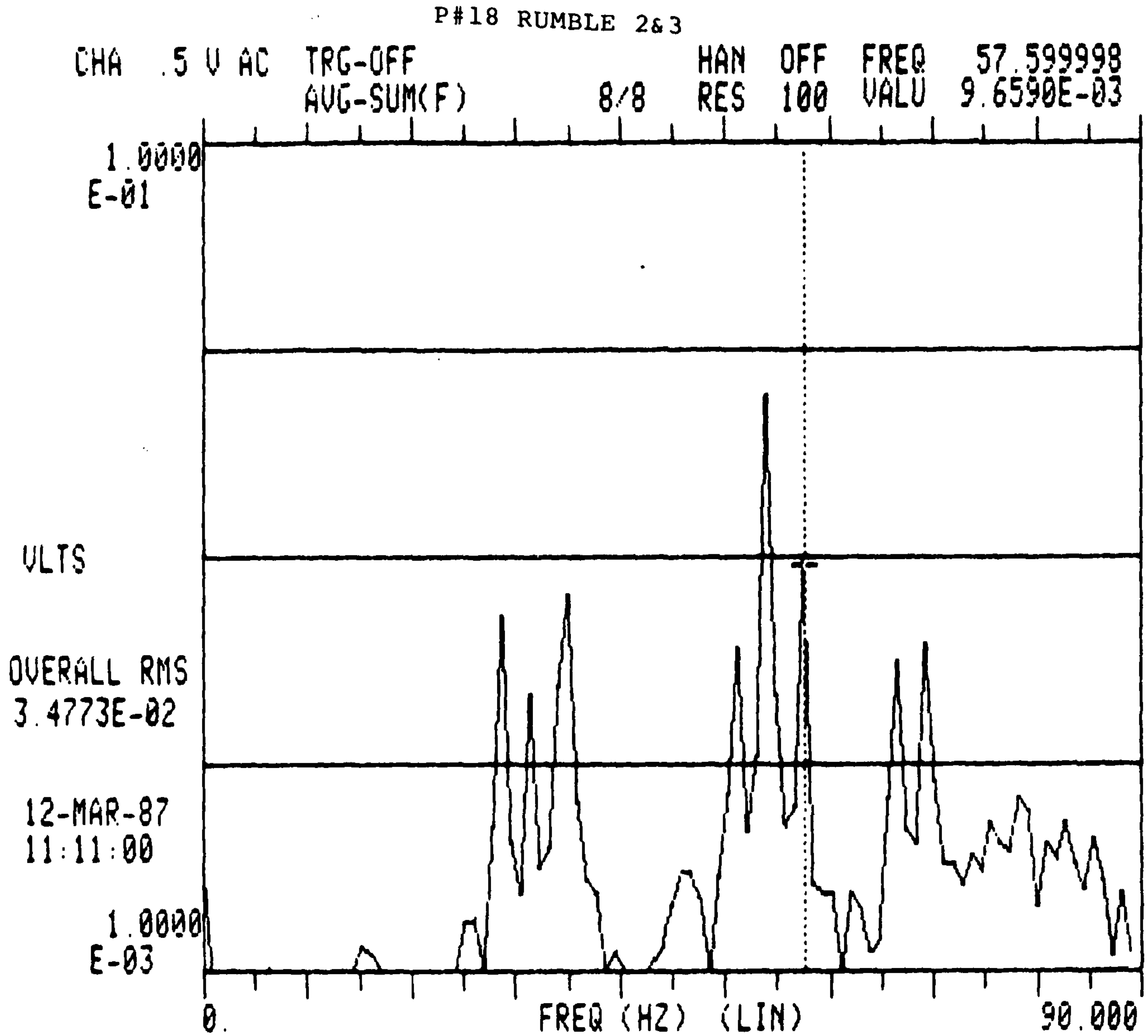
P#14 RUMBLE 2&3



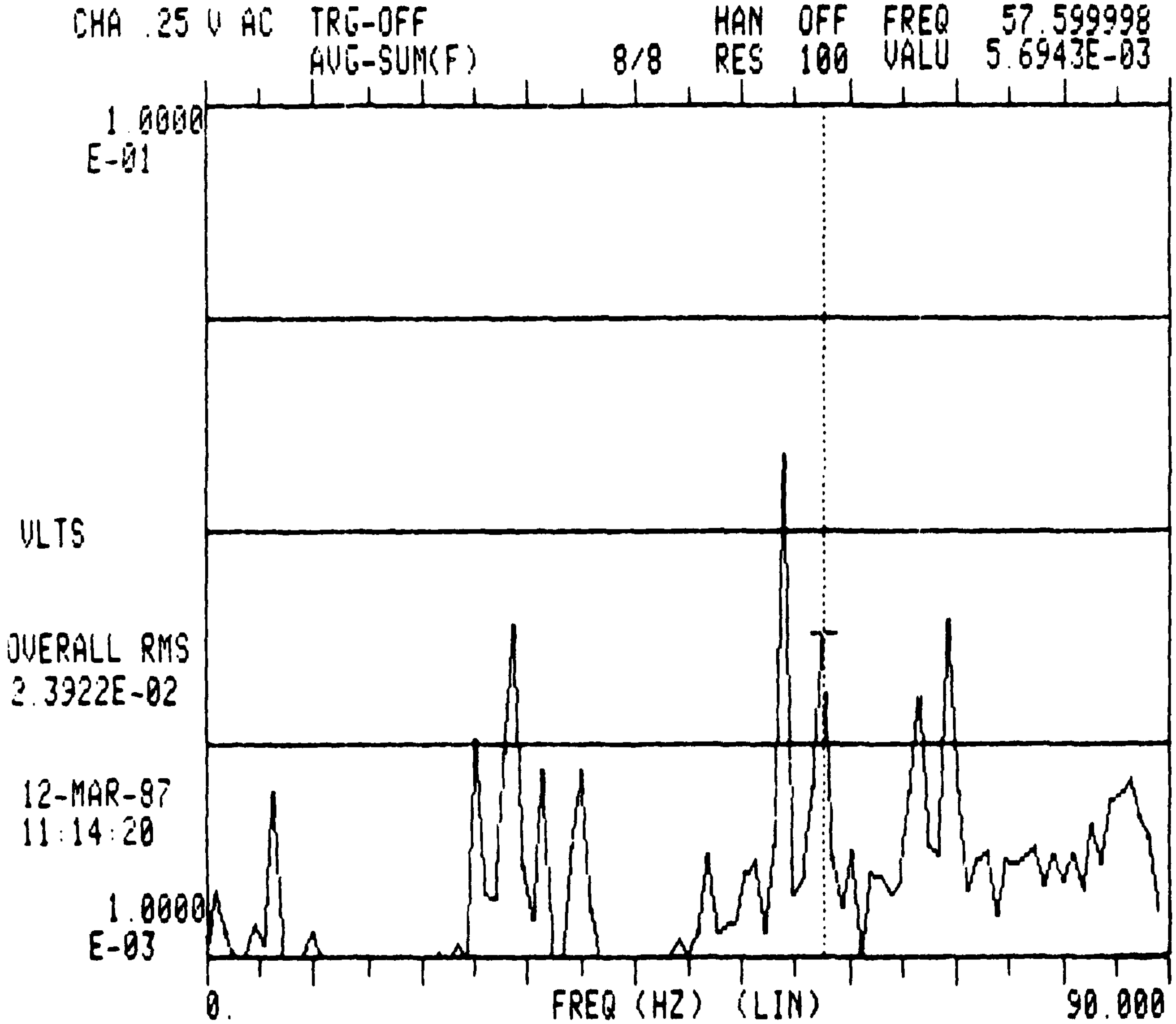
P#15 RUMBLE 2&3

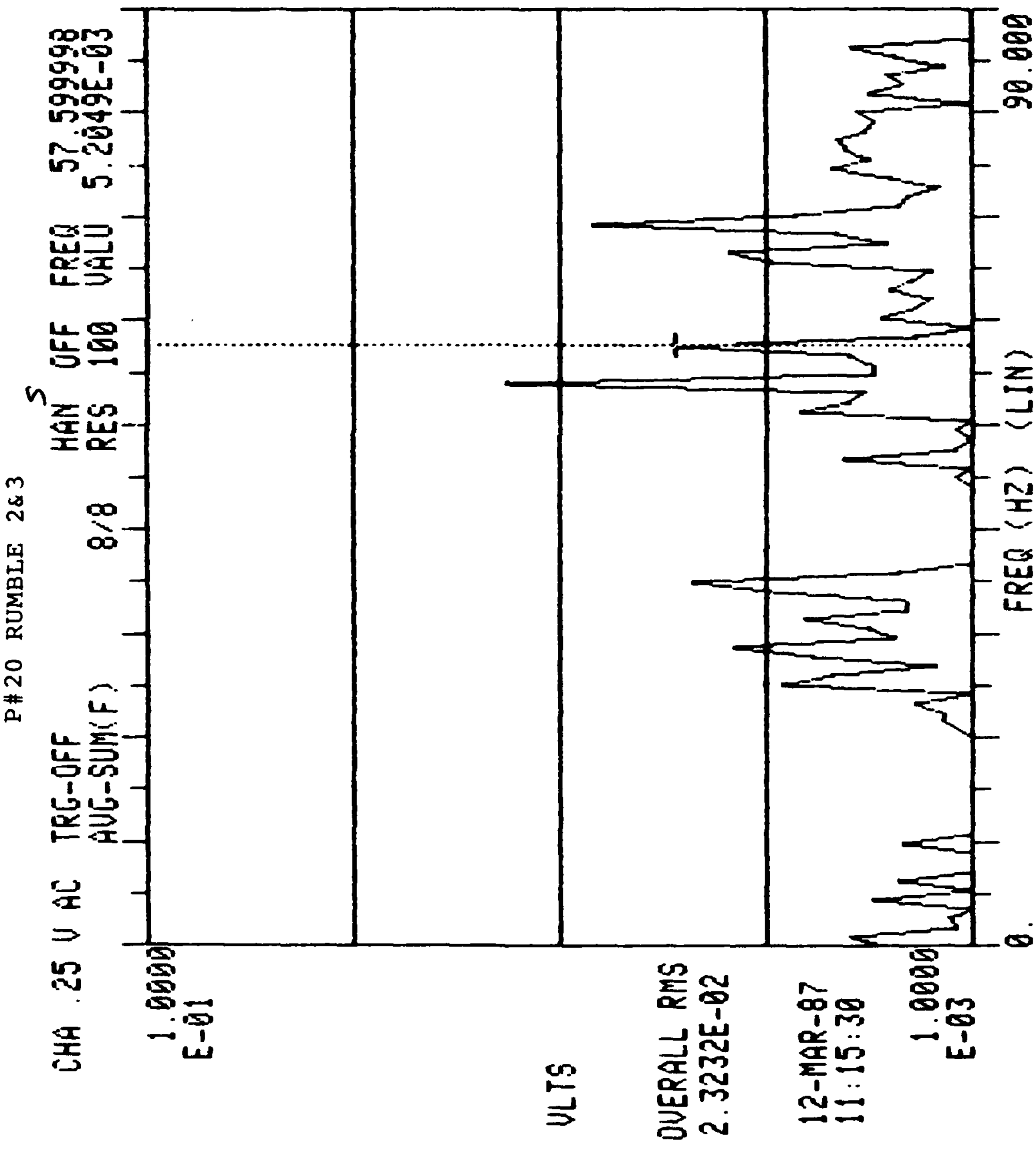



P#17 RUMBLE 2&3
CHB .5 V AC TRG-OFF
AVG-SUM(F)
8/8
HAN OFF FREQ 57.599998
RES 100 VALU 2.9536E-04
1.0000
E-03
VLTS
OVERALL RMS
1.5072E-03
12-MAR-87
11:08:30
1.0000
E-05
0.
FREQ (HZ) (LIN)
90.000

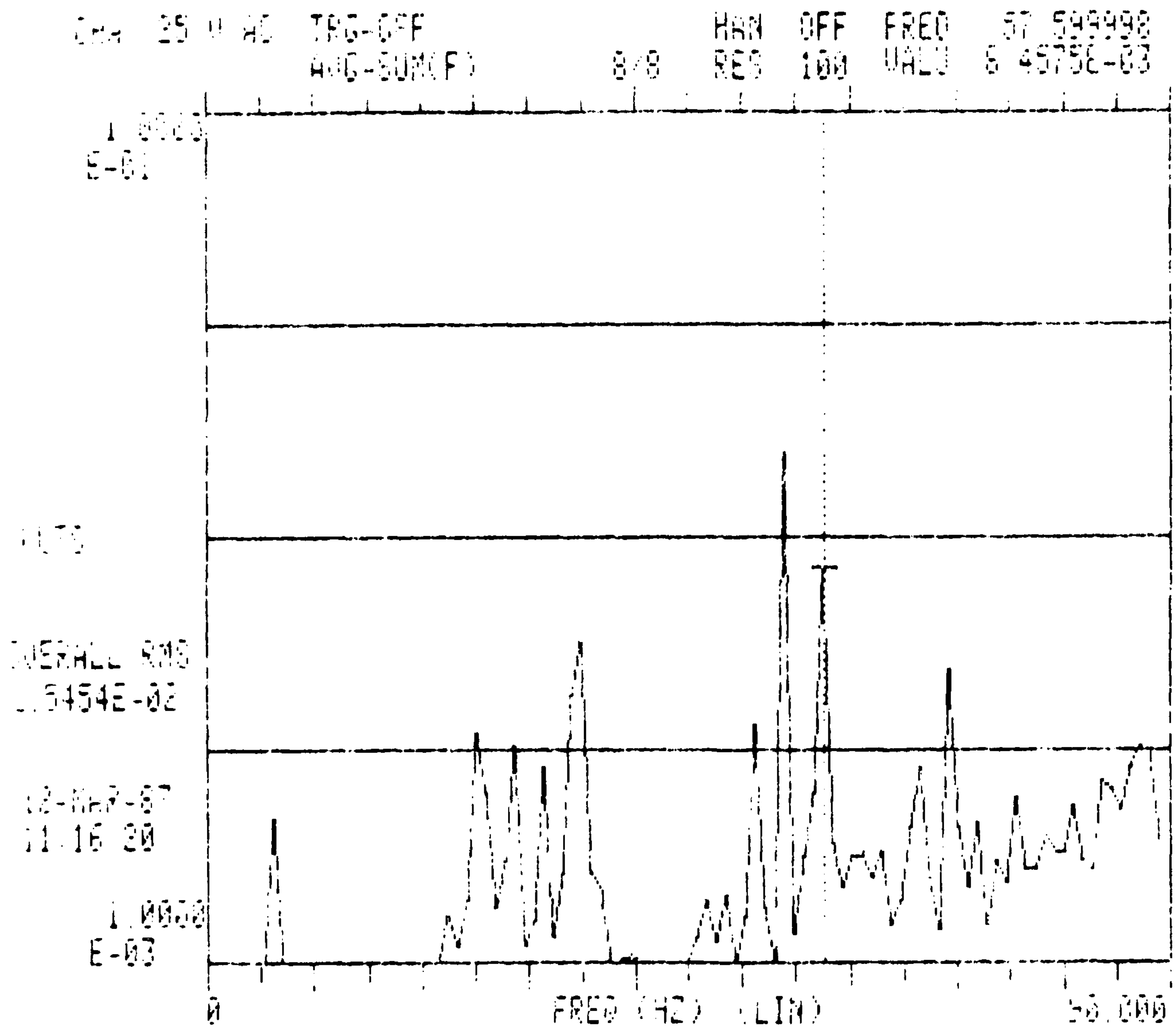

P#18 RUMBLE 2&3
CHA .5 V AC TRG-OFF HAN OFF FREQ 57.599998
AVG-SUM(F) 8/8 RES 100 VALU 9.6590E-03
1.0000
E-01
VLTS
OVERALL RMS
3.4773E-02
12-MAR-87
11:11:00
1.0000
E-03
0.
FREQ (HZ) (LIN)
90.000

P#19 RUMBLE 2&3

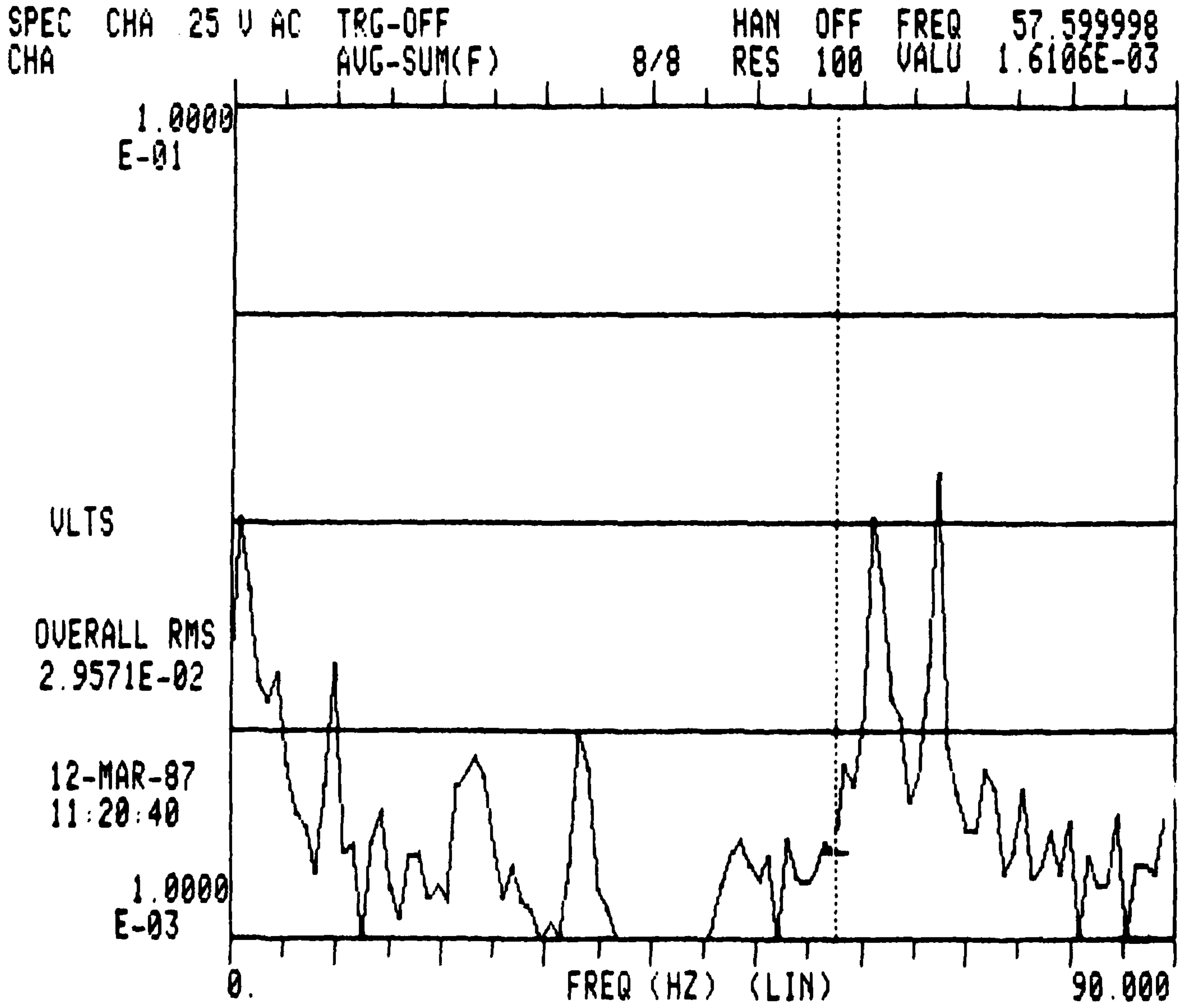



P#20 RUMBLE 2&3
CHA .25 V AC
TRG-OFF
AVG-SUM(F)
8/8
HAN
RES
OFF
100
FREQ
VALU
57.599998
5.2049E-03
1.0000
E-01
VLTS
OVERALL RMS
2.3232E-02
12-MAR-87
11:15:30
1.0000
E-03
0.
90.000
FREQ (HZ) (LIN)

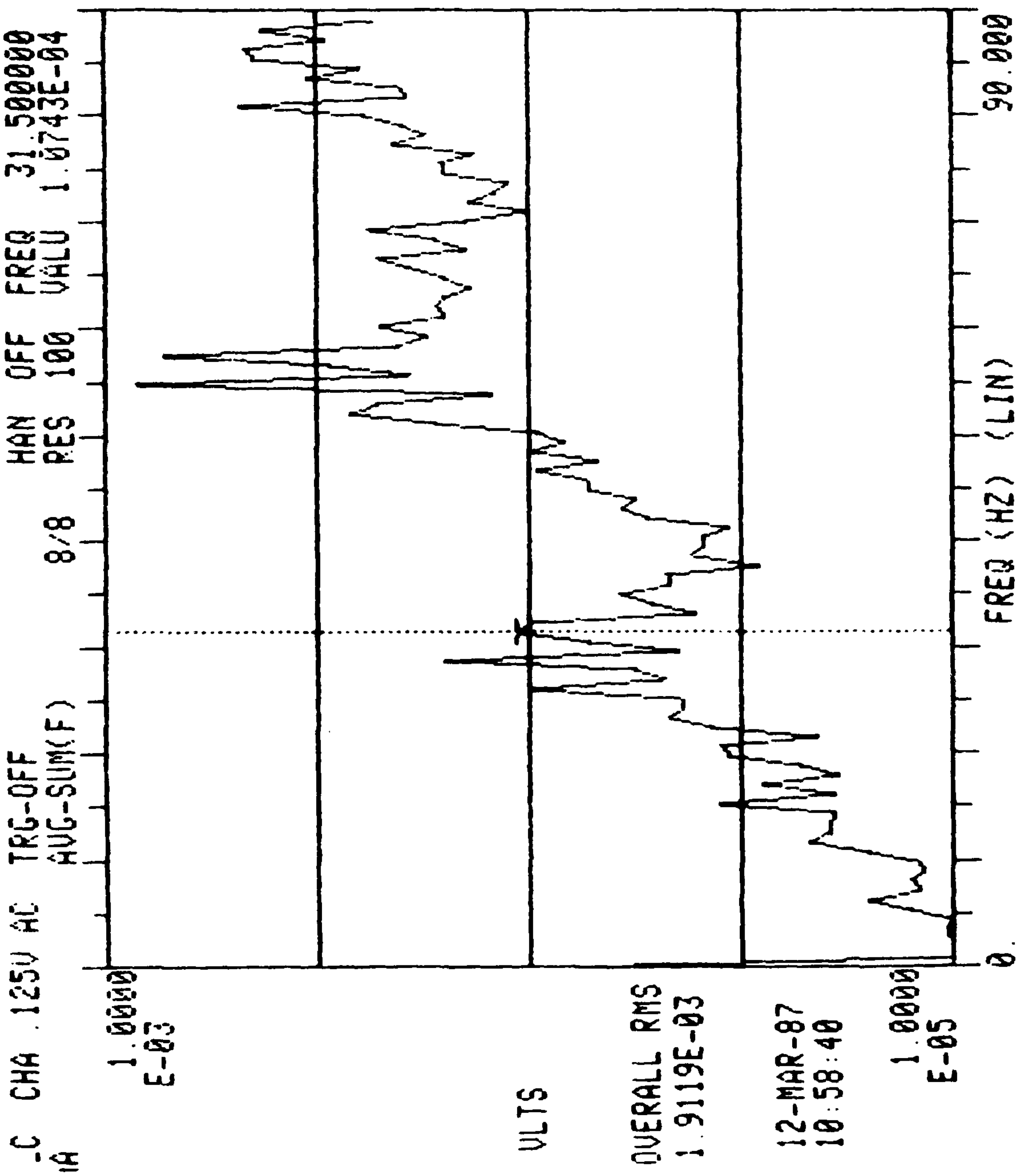
P#21 RUMBLE 2&3



P#20N NO RUMBLE

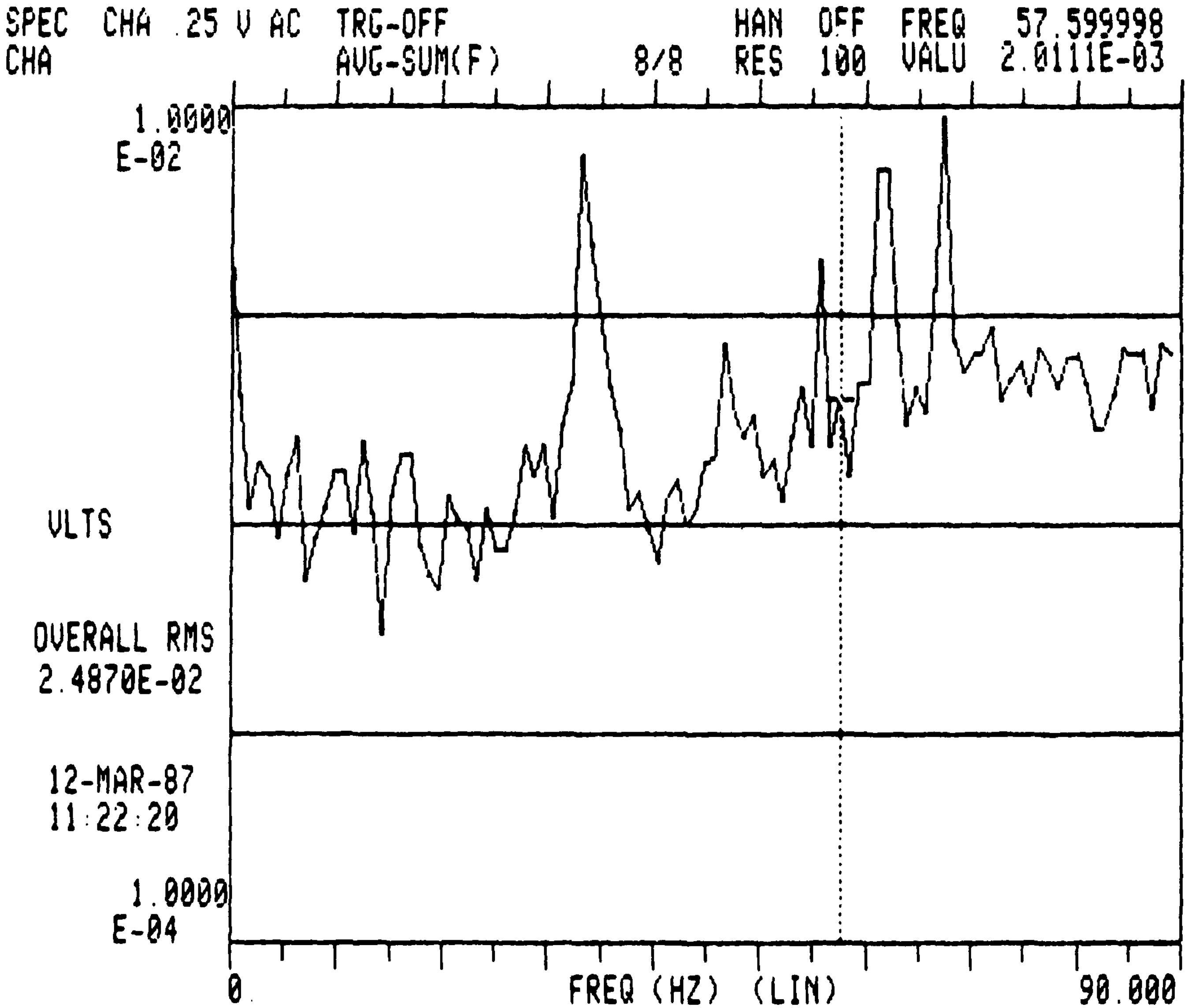


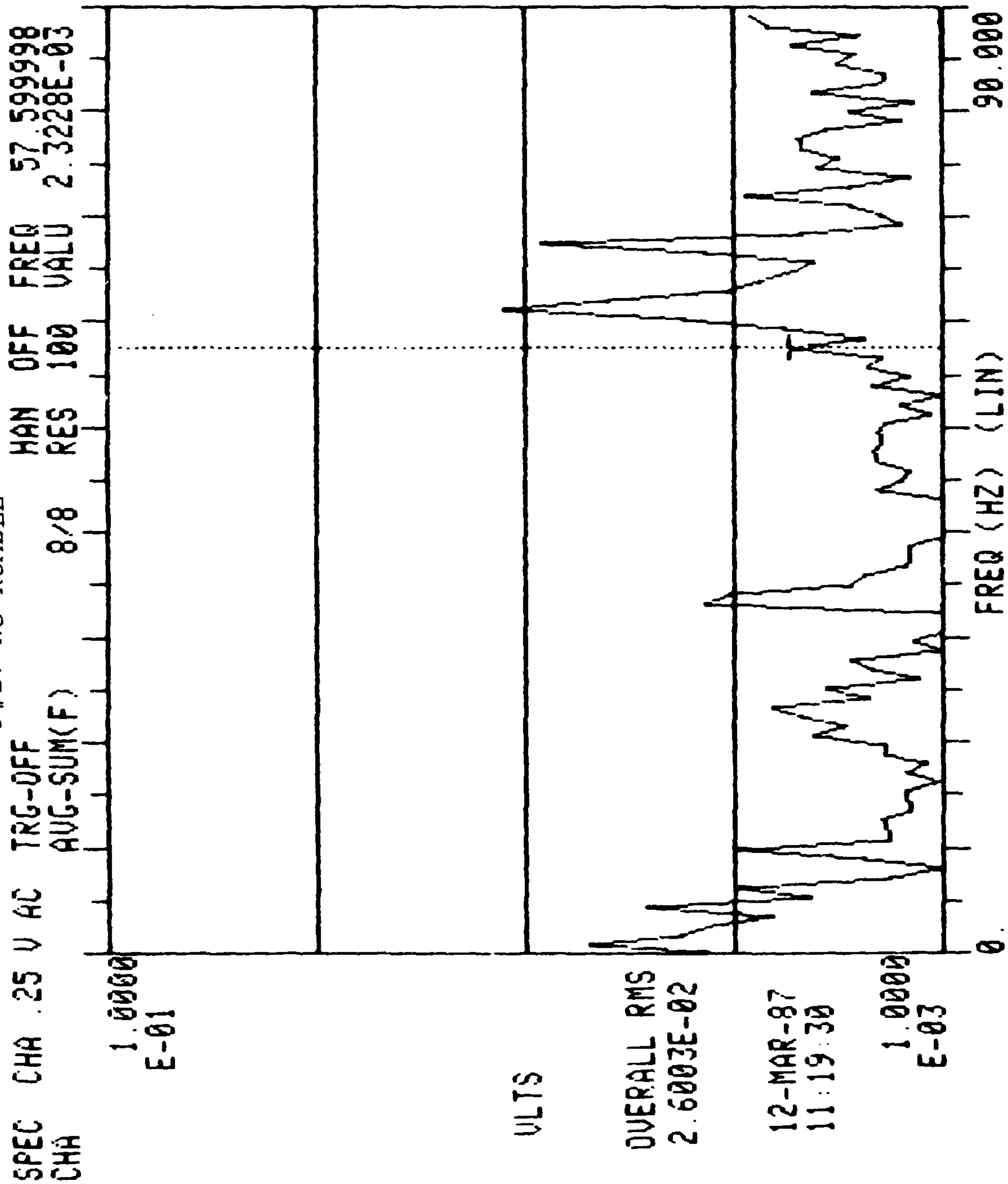
P#5 RUMBLE 1



CHA .125V AC
TRG-OFF
AVG-SUM(F)
8/8
HAN OFF
RES 100
FREQ 31.500000
VALU 1.07743E-04
1.0000
E-03
VLTS
OVERALL RMS
1.9119E-03
12-MAR-87
10:58:40
1.0000
E-05
0
90.000
FREQ (HZ) (LIN)

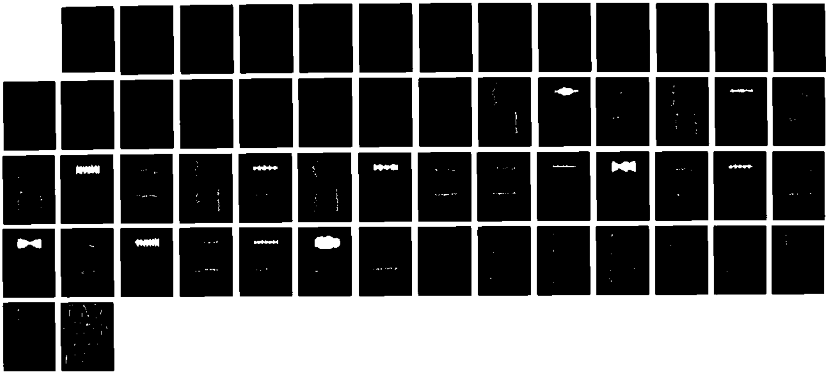
P#17 NO RUMBLE

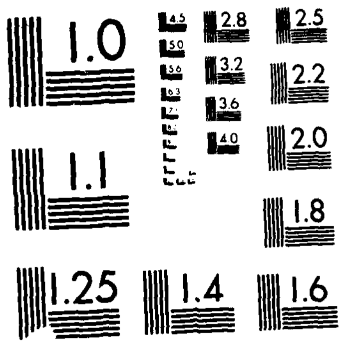



P#17 NO RUMBLE
SPEC CHA .25 V AC TRG-OFF 8/8 HAN OFF FREQ 57.599998
CHA AVG-SUM(F) RES 100 VALU 2.3228E-03
1.0000 E-01
VLTS
OVERALL RMS 2.6003E-02
12-MAR-87 11:19:30
1.0000 E-03
0
90.000
FREQ (HZ) (LIN)

AD-A207 532 KC-135R RUMBLE INVESTIGATION(U) DAYTON UNIV OH RESEARCH 3/3
INST M L DRAKE ET AL. 27 FEB 89 UDR-TR-88-04
AFWAL-TR-88-4260 F33615-85-C-5040

UNCLASSIFIED F/G 1/3.5 NL



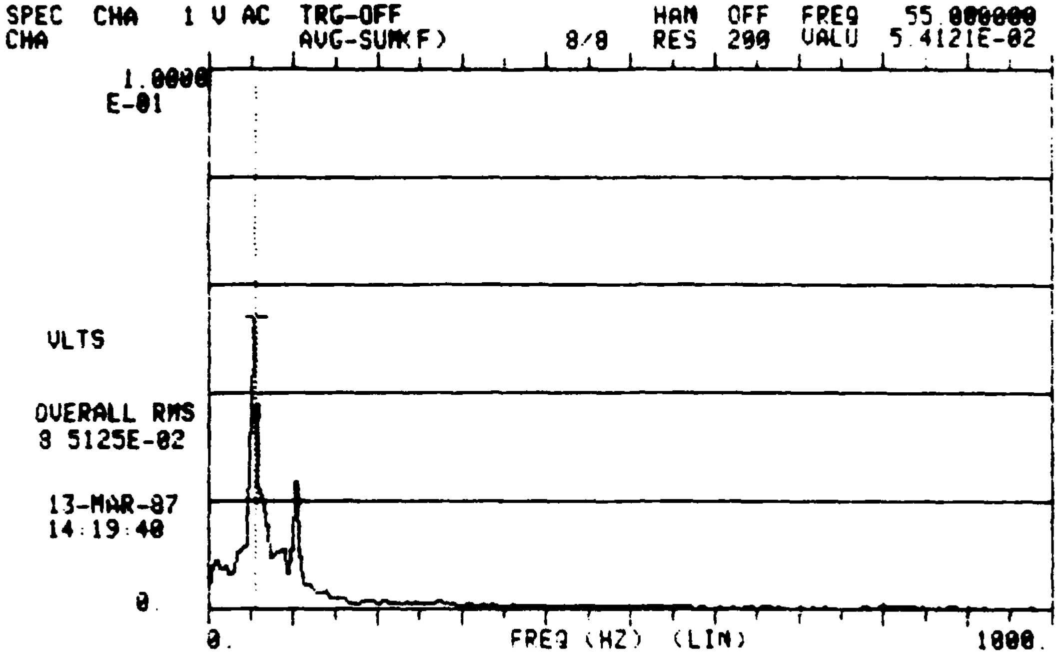


UTION TEST CHART

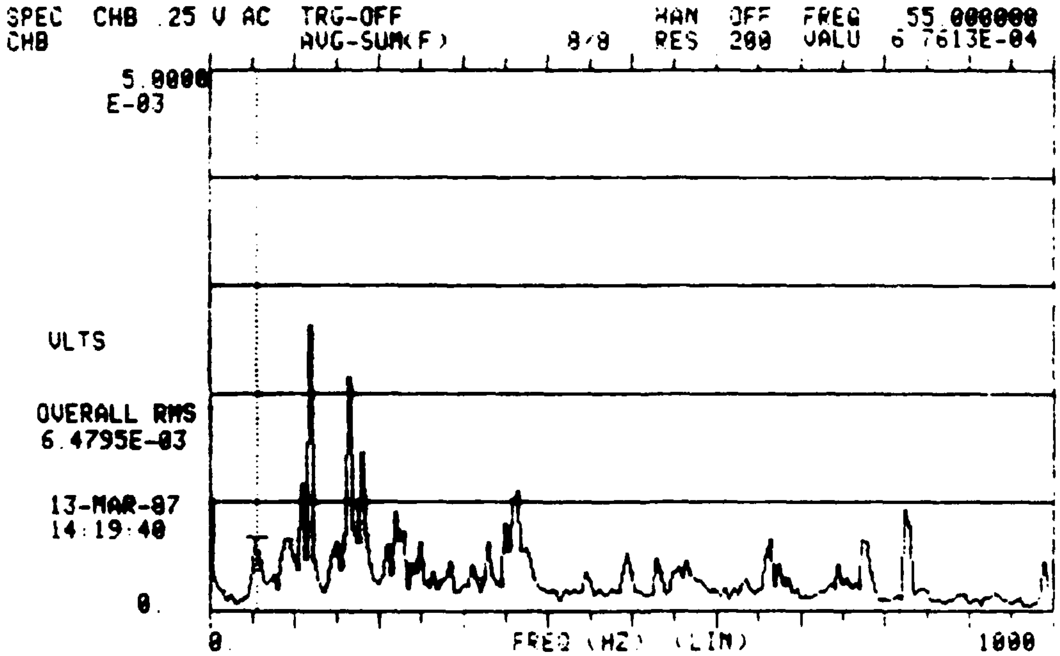
APPENDIX D

DATA POINTS FOR GROUND TEST

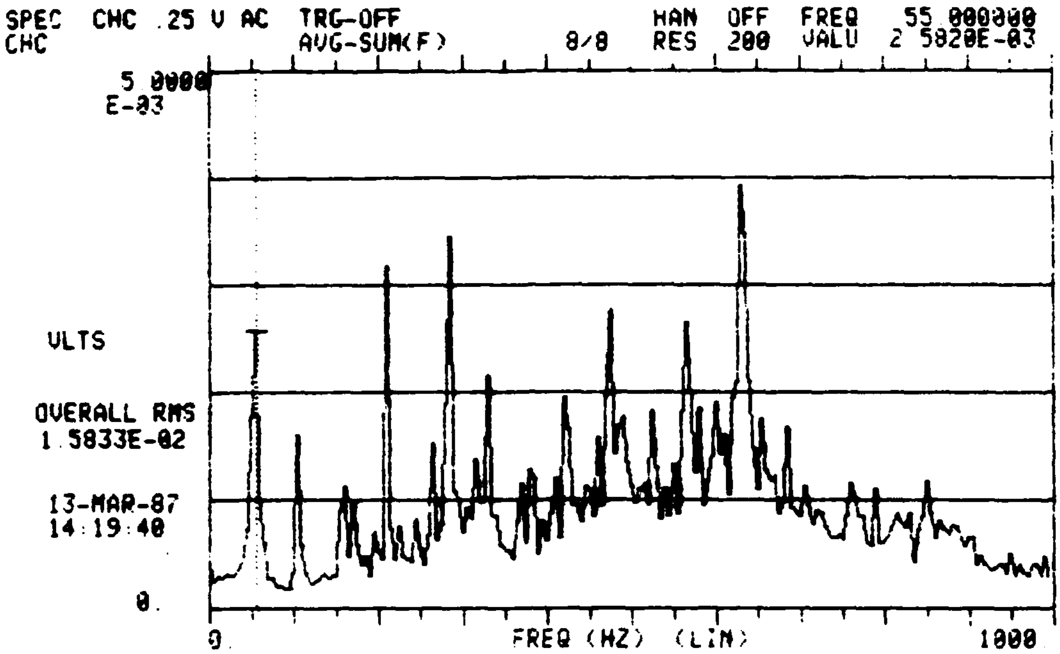
G-21K3 P#1 at 61.5%



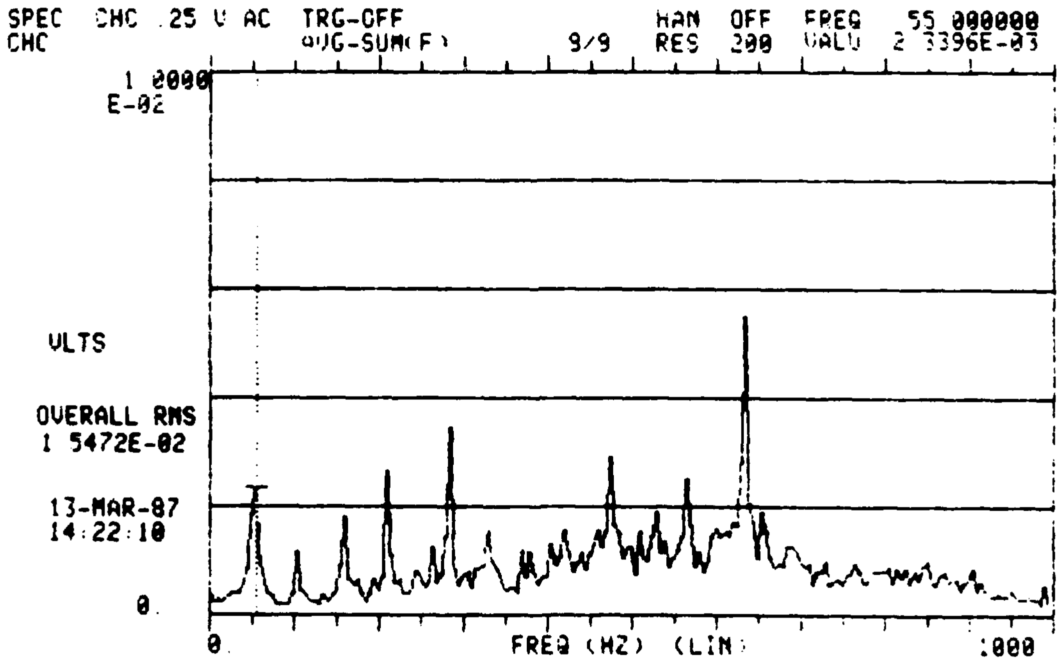
G-21K3 P#2 at 61.5%



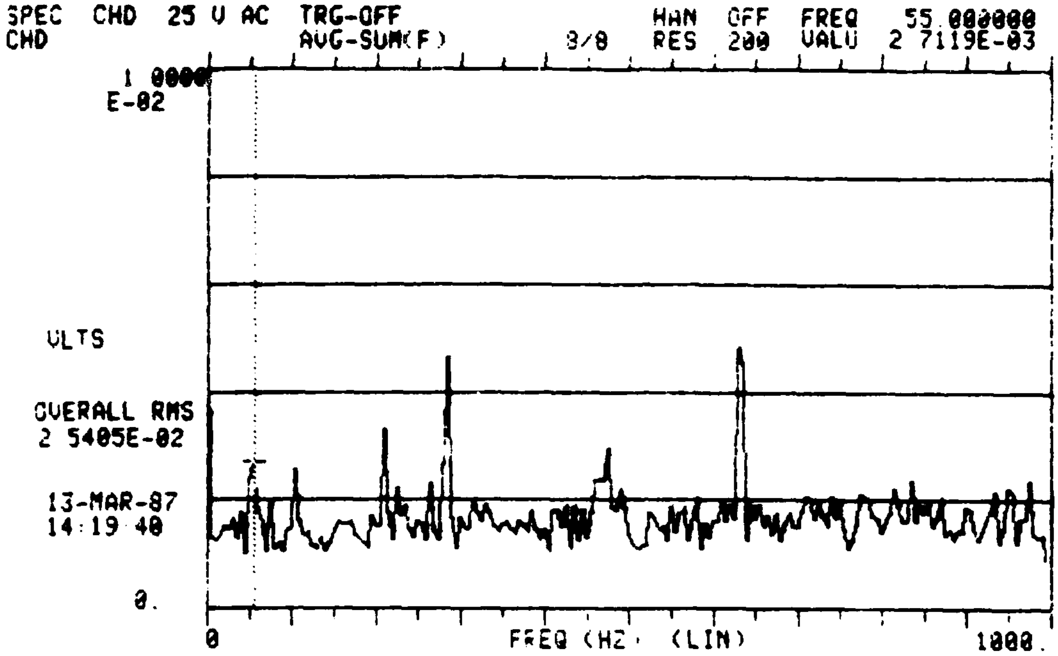
G-21K3 P#3 at 61.5%



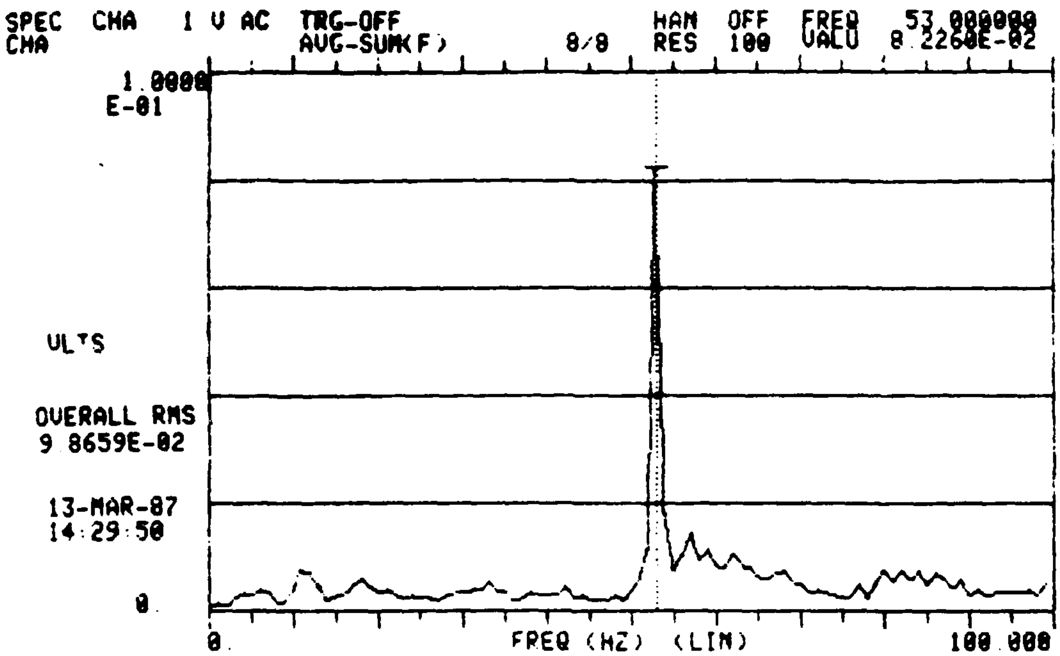
G-21K3 P#4 at 61.5%



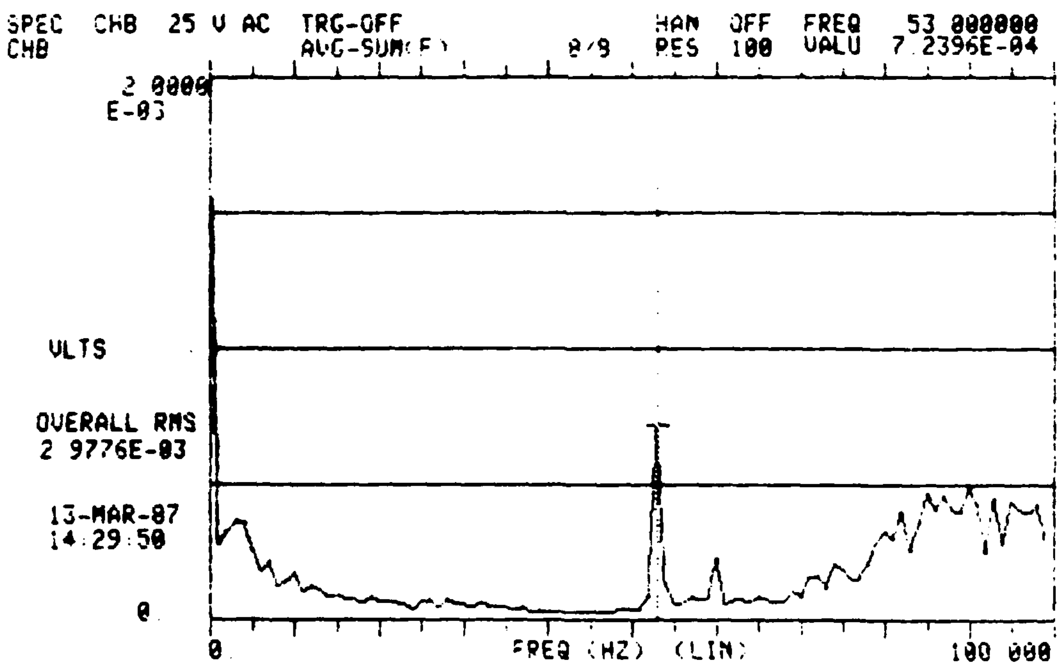
G-21K3 P#5 at 61.5%



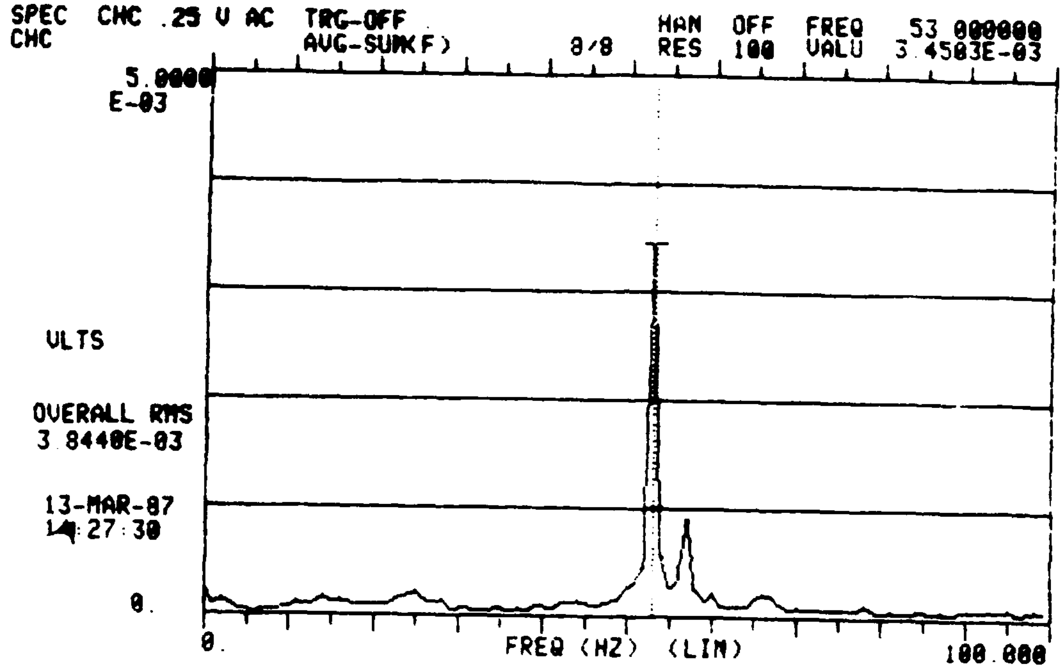
G-21K4 P#1 at 61.5%



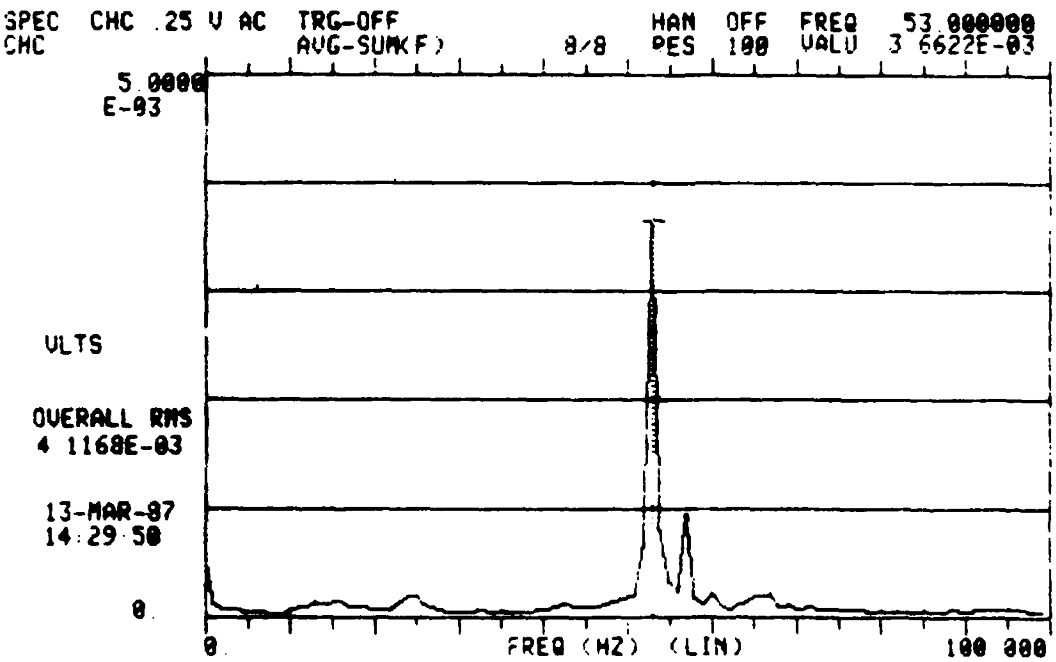
G-21K4 P#2 at 61.5%



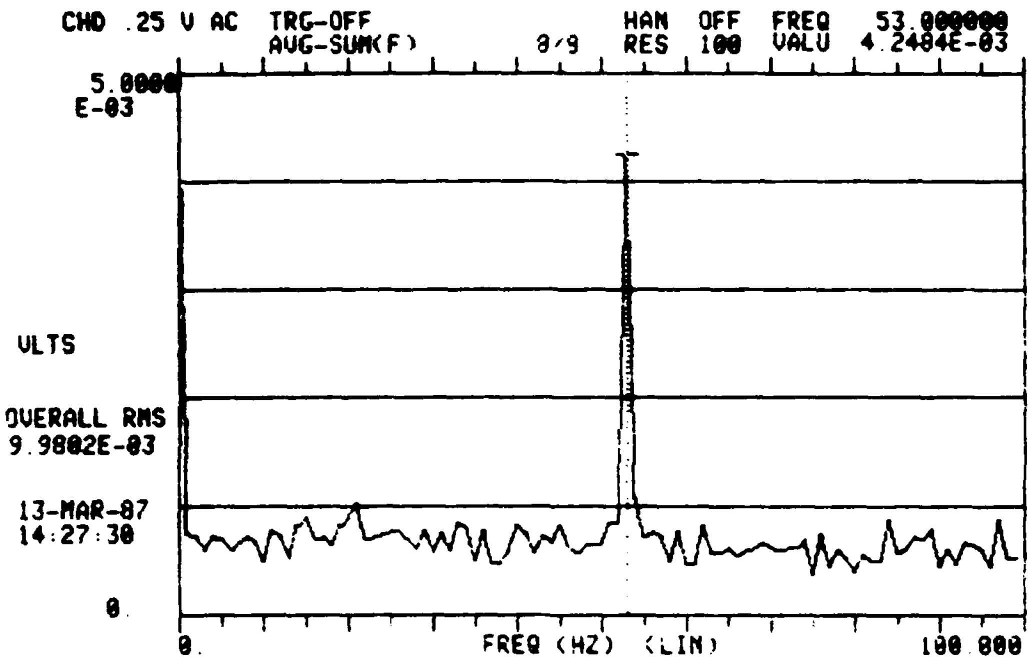
G-21K4 P#3 at 61.5%



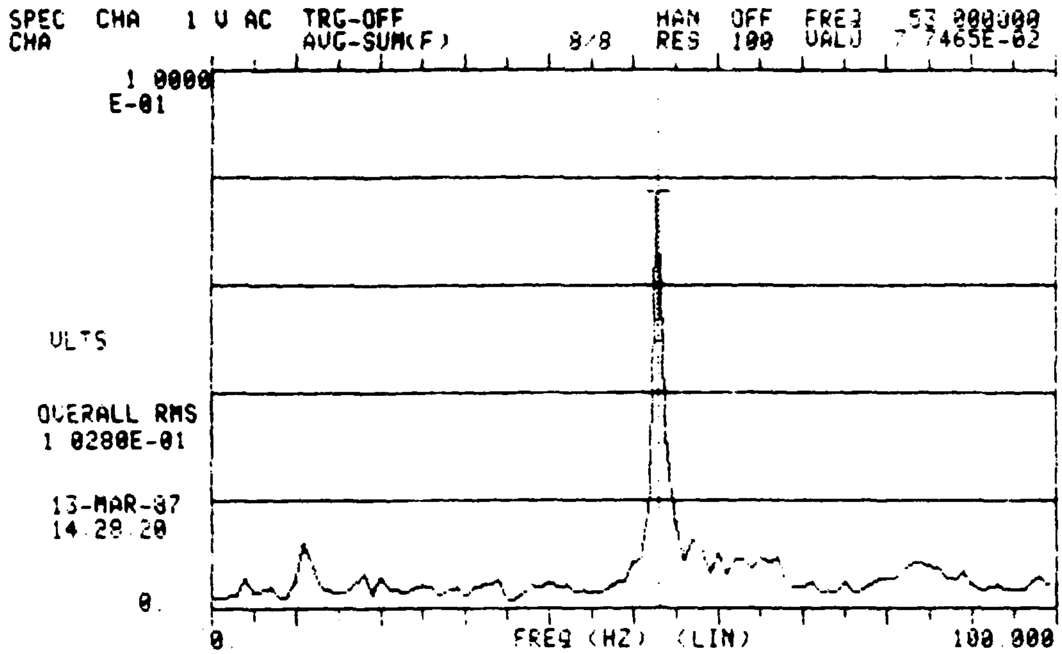
G-21K4 P#4 at 61.5%



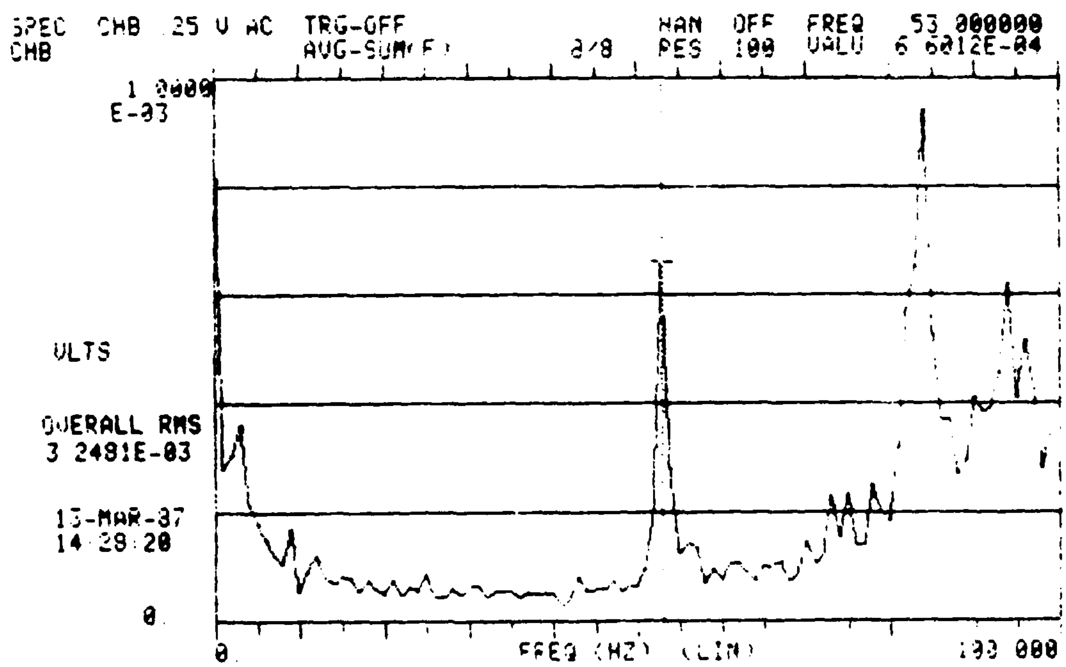
G-21K4 P#5 at 61.5%



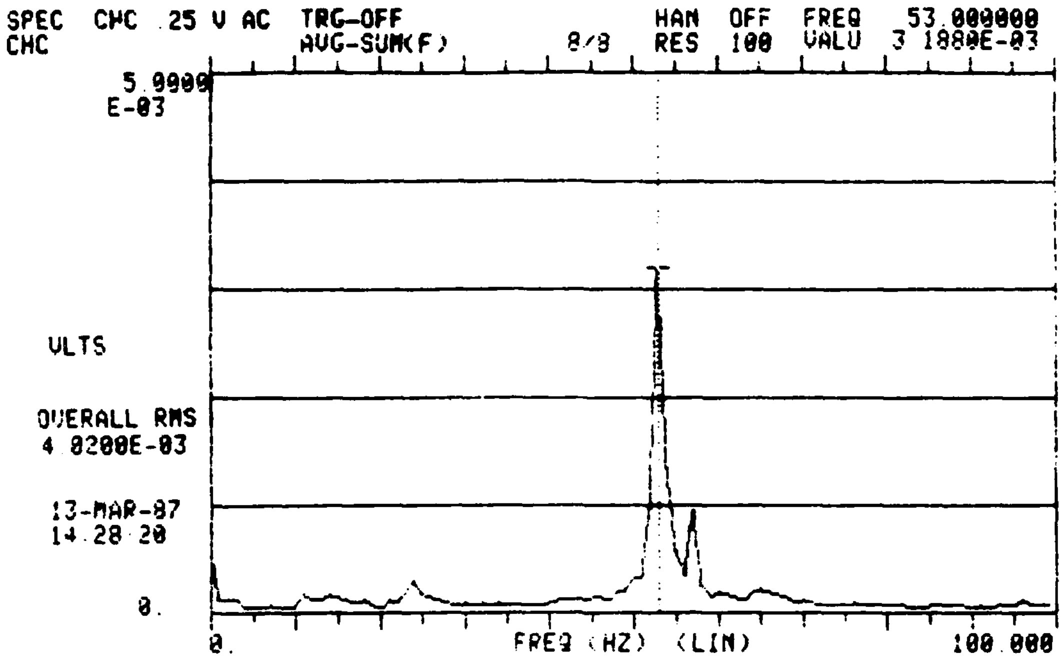
G-23R P#1 at 61.5%



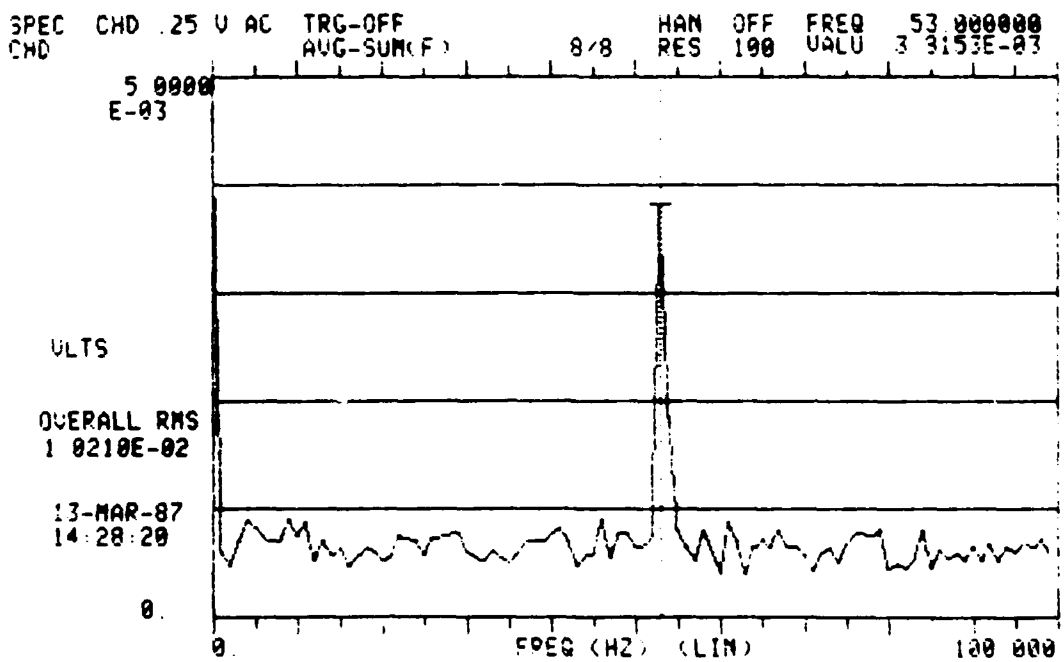
G-23R P#2 at 61.5%



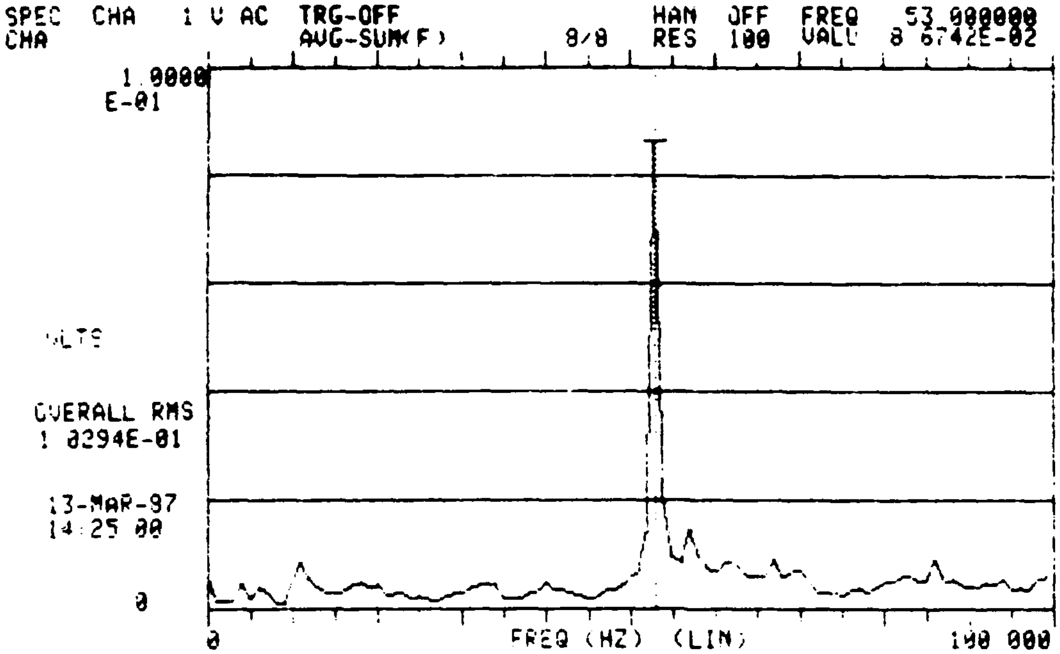
G-23R P#3 at 61.5%



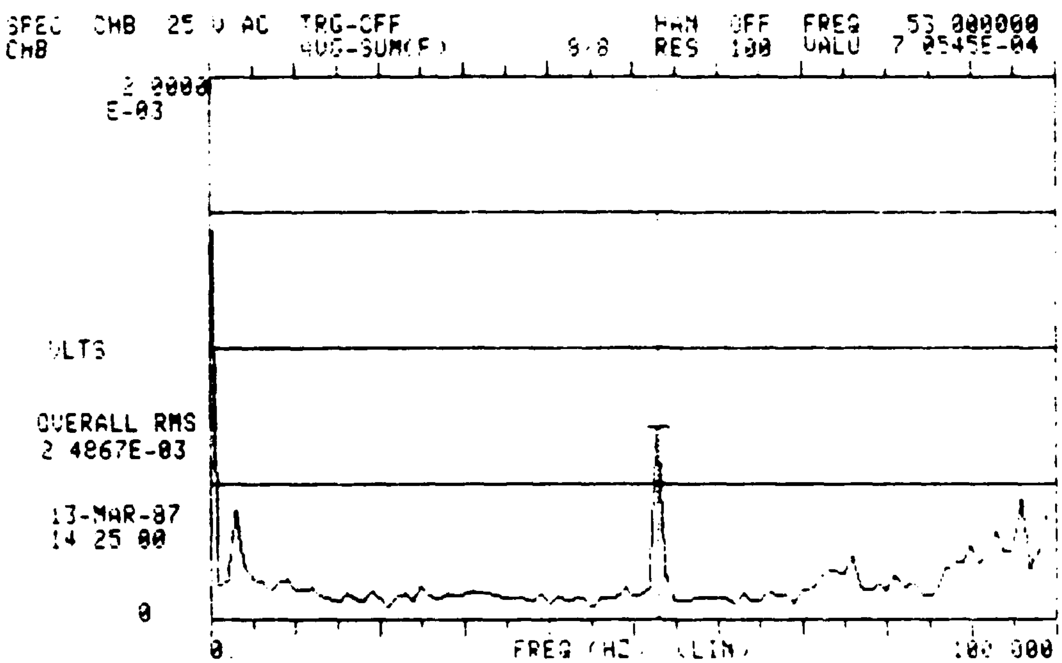
G-23R P#5 at 61.5%



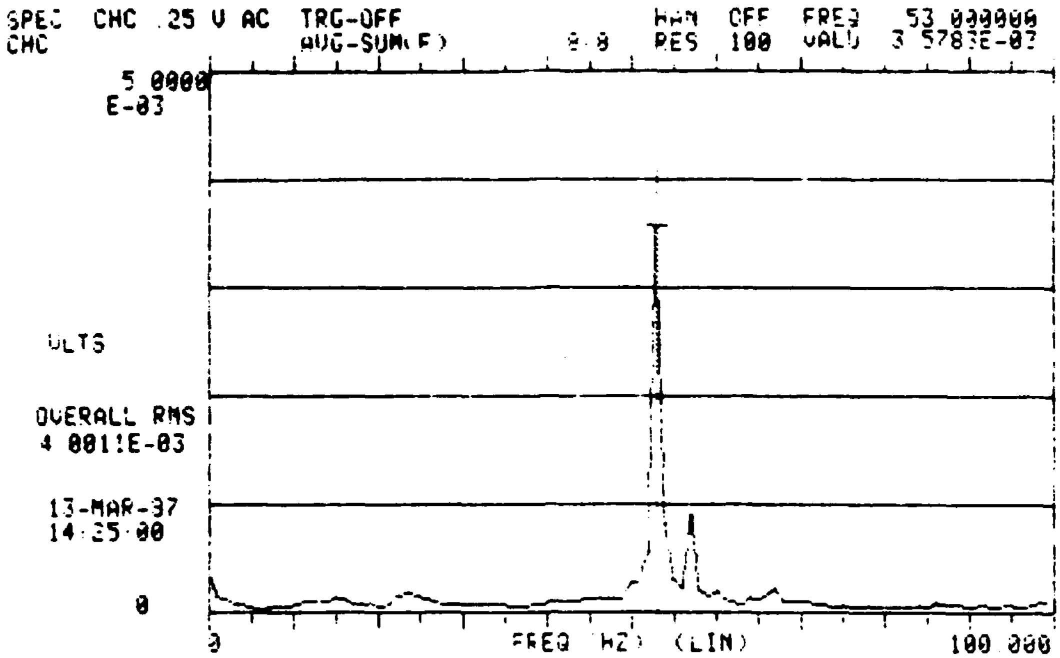
G-24 P#1 at 61.5%



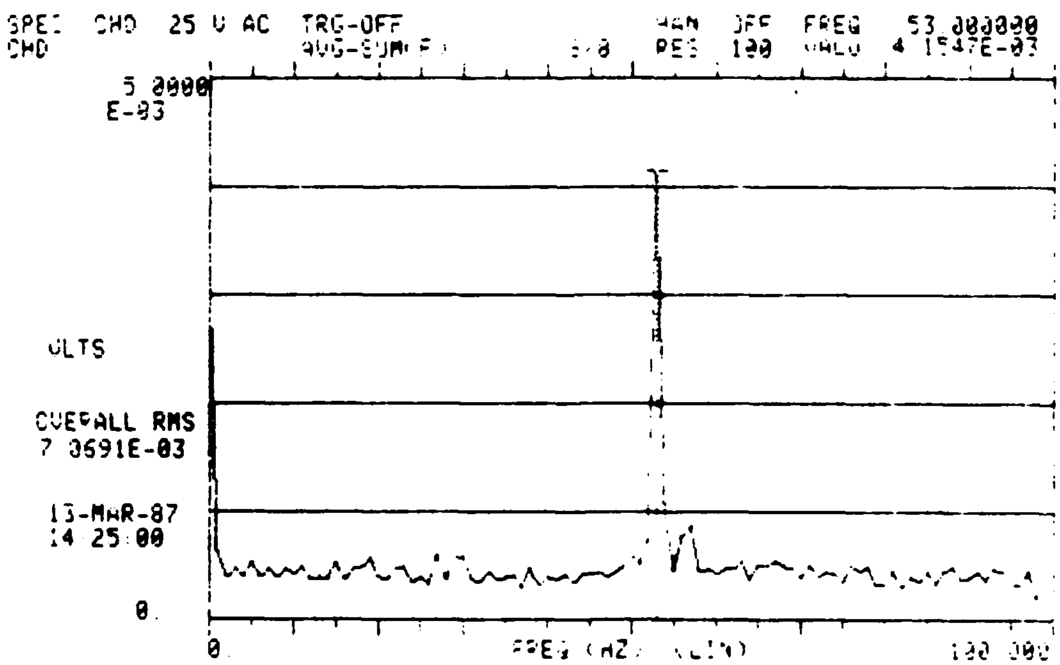
G-24 P#2 at 61.5%



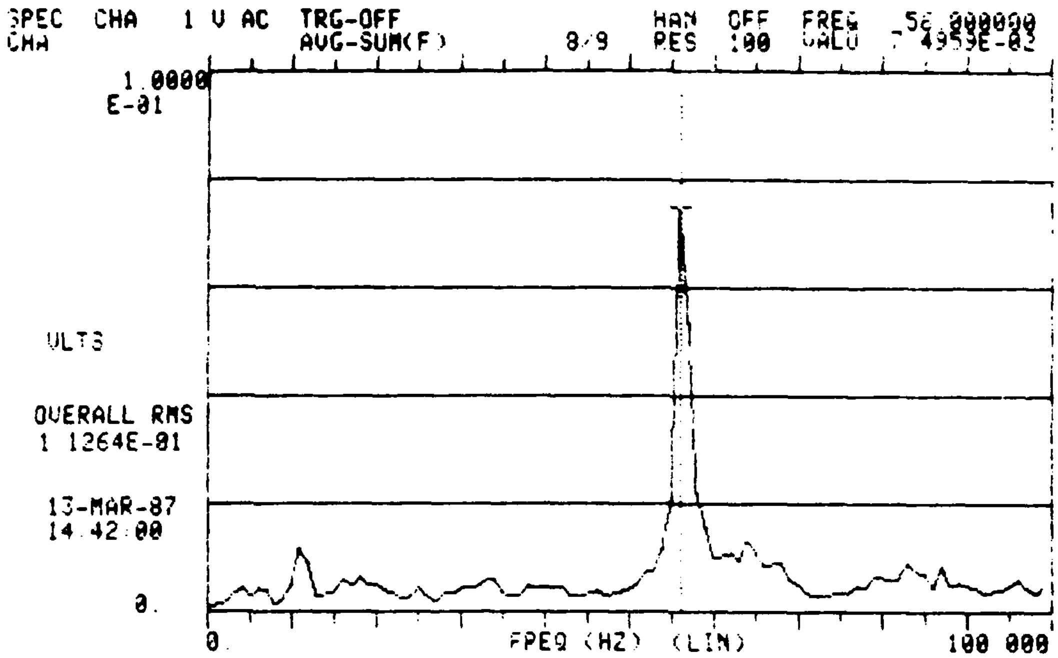
G-24 P#4 at 61.5%



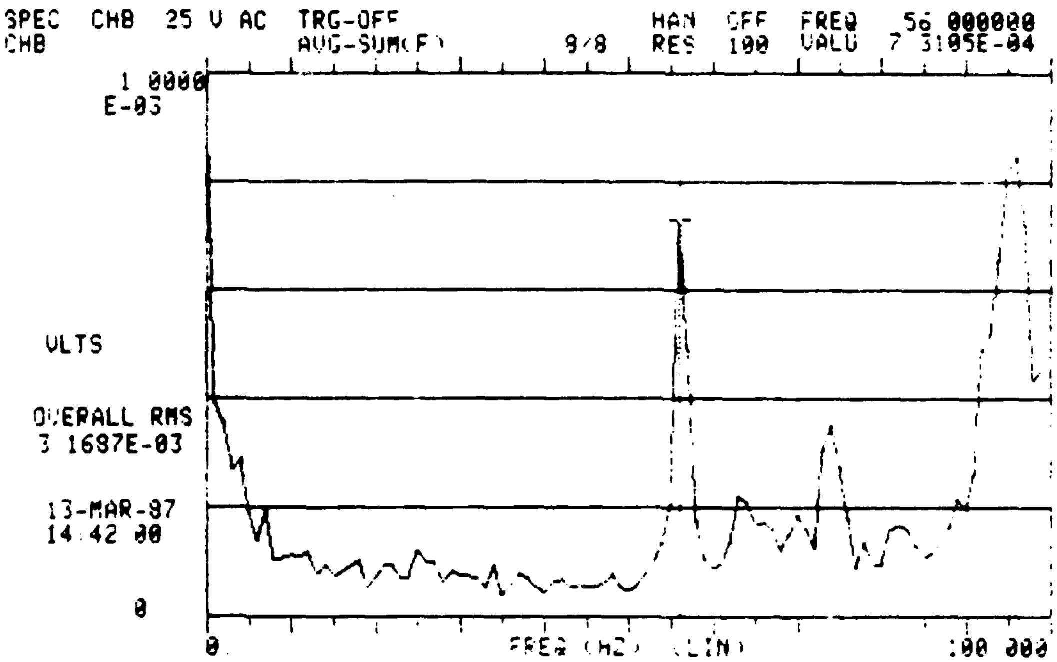
G-24 P#5 at 61.5%



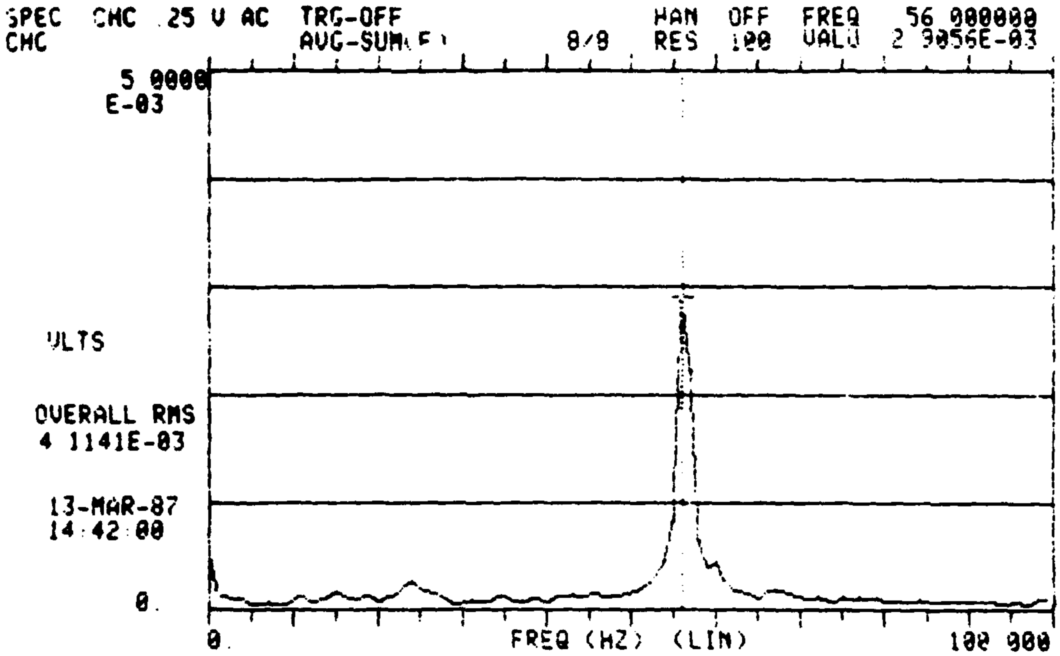
G-33 P#1 at 65.5%



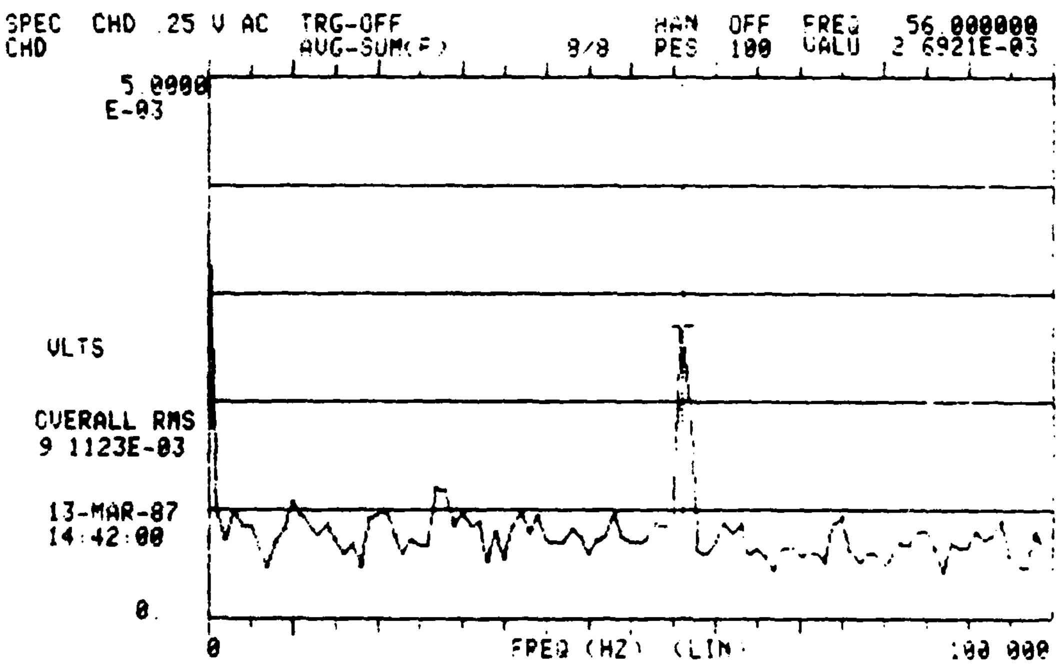
G-33 P#2 at 65.5%



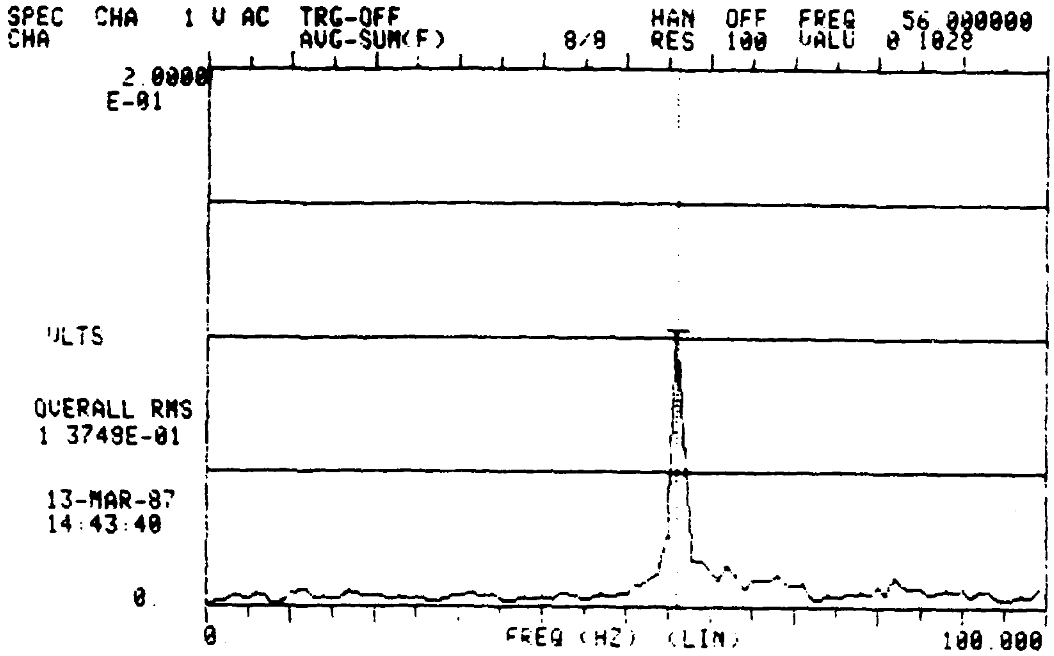
G-33 P#3 at 65.5%



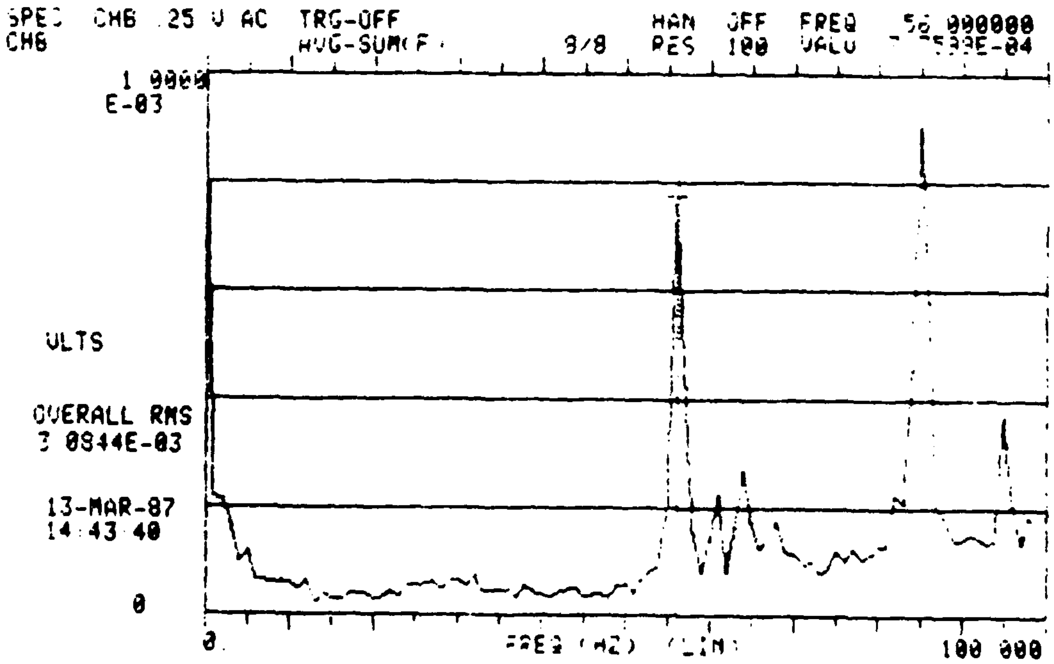
G-33 P#5 at 65.5%



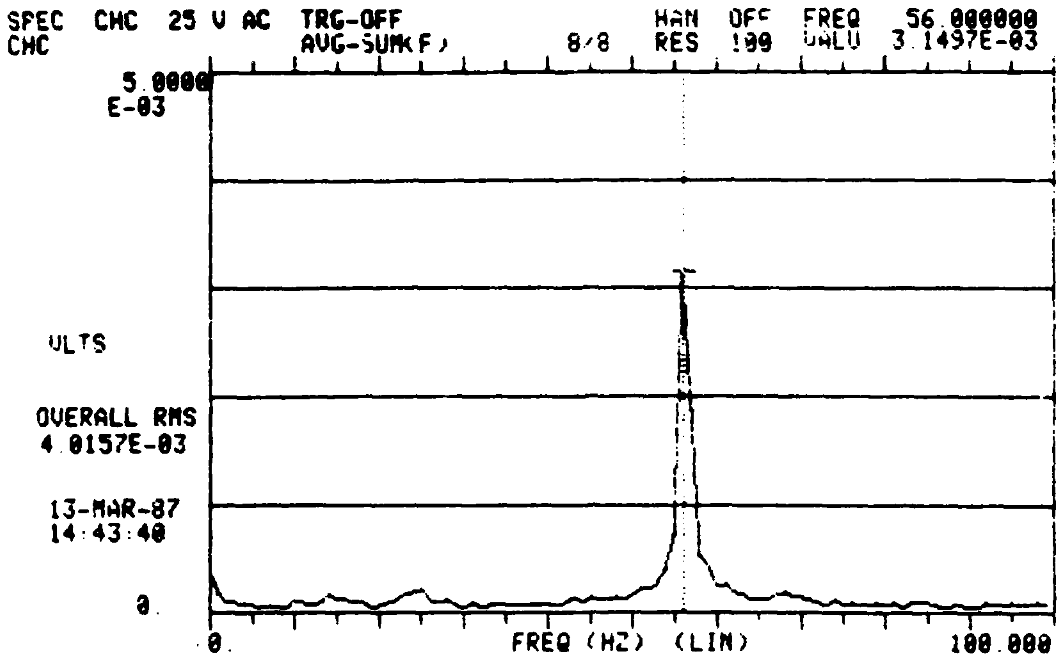
G-34 P#1 at 65.5%



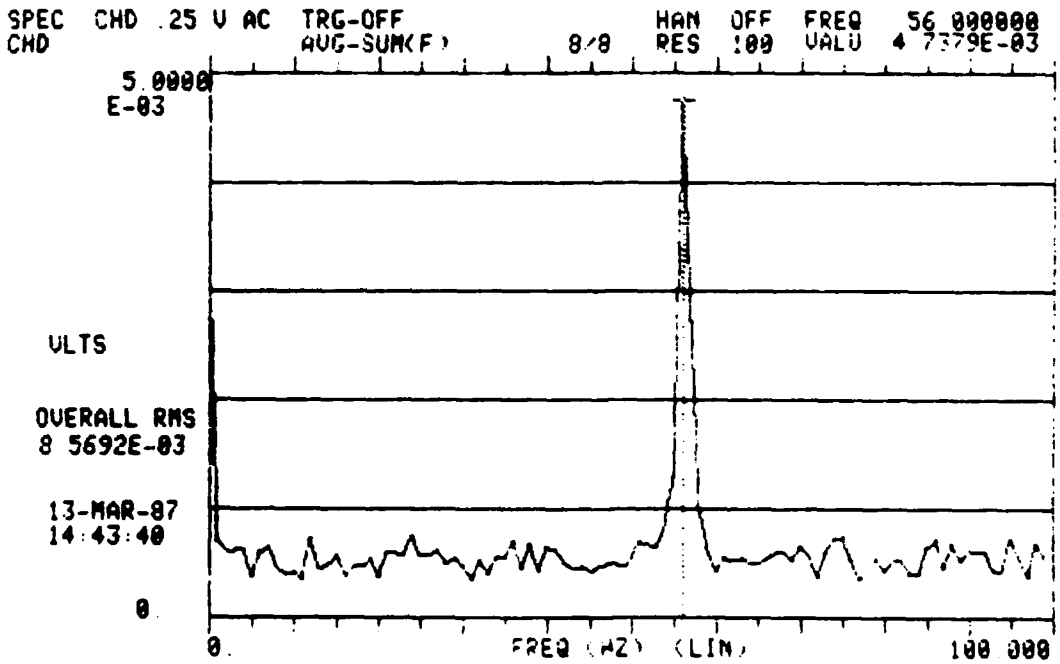
G-34 P#2 at 65.5%



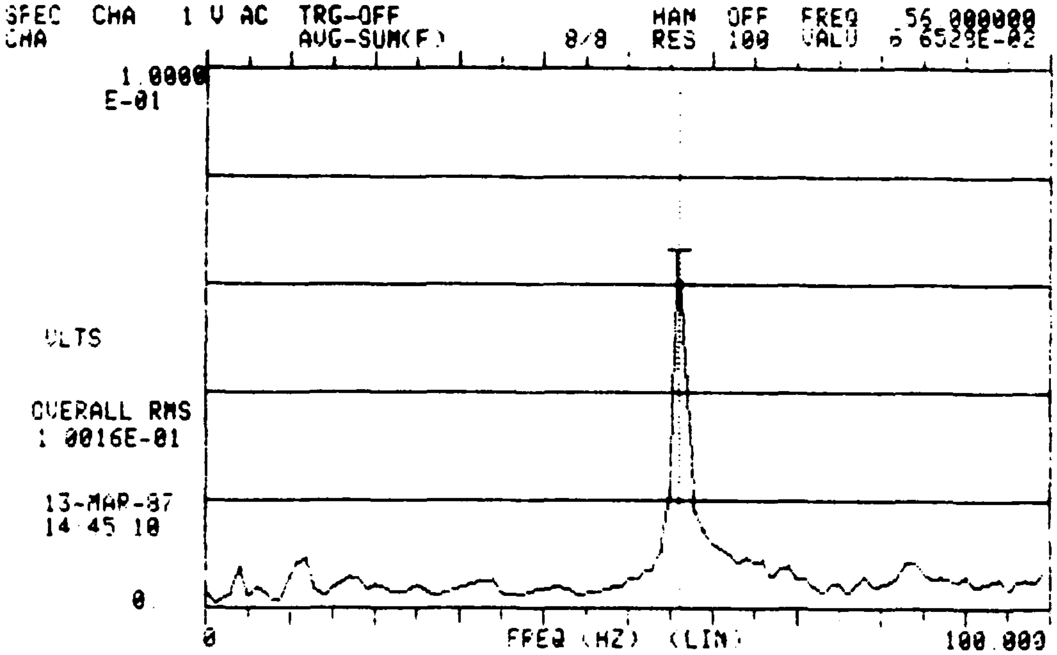
G-34 P#4 at 65.5%



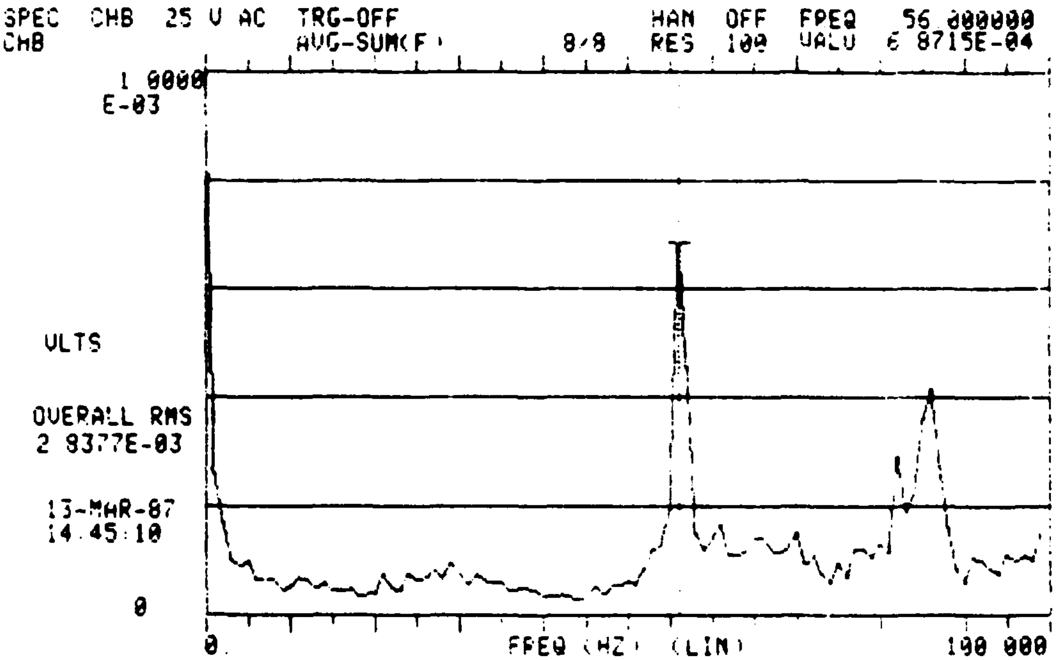
G-34 P#5 at 65.5%



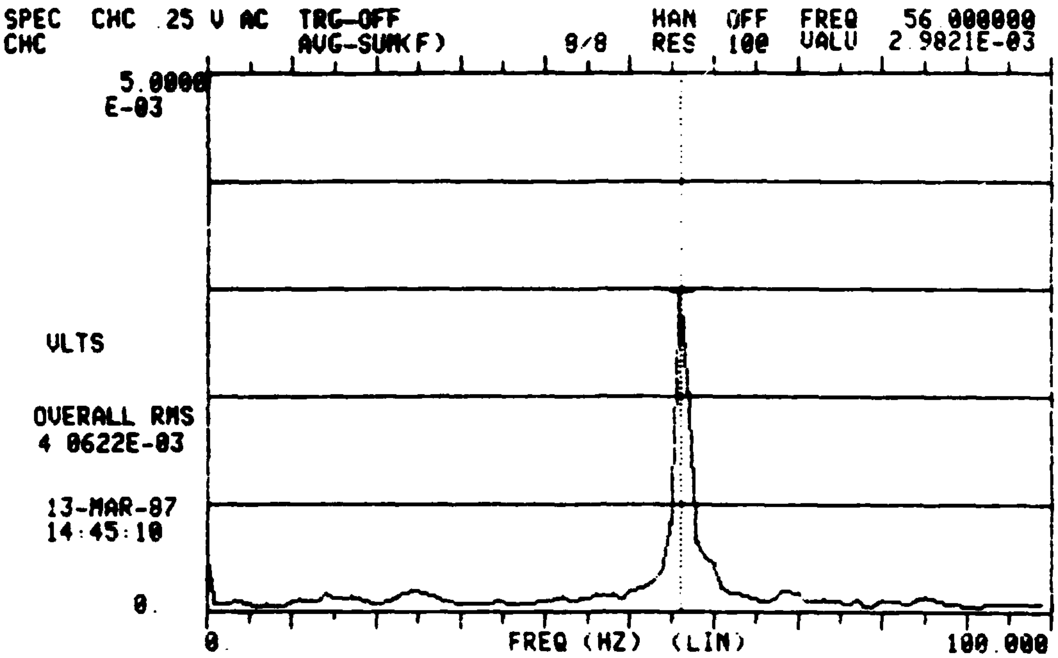
G-34R P#1 at 65.5%



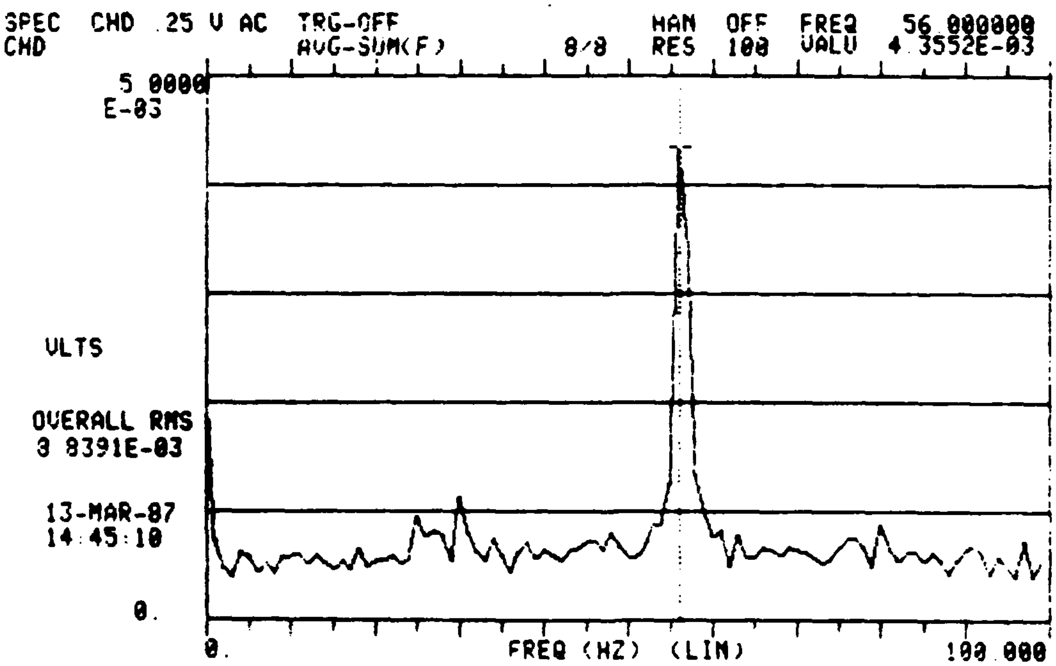
G-34R P#2 at 65.5%



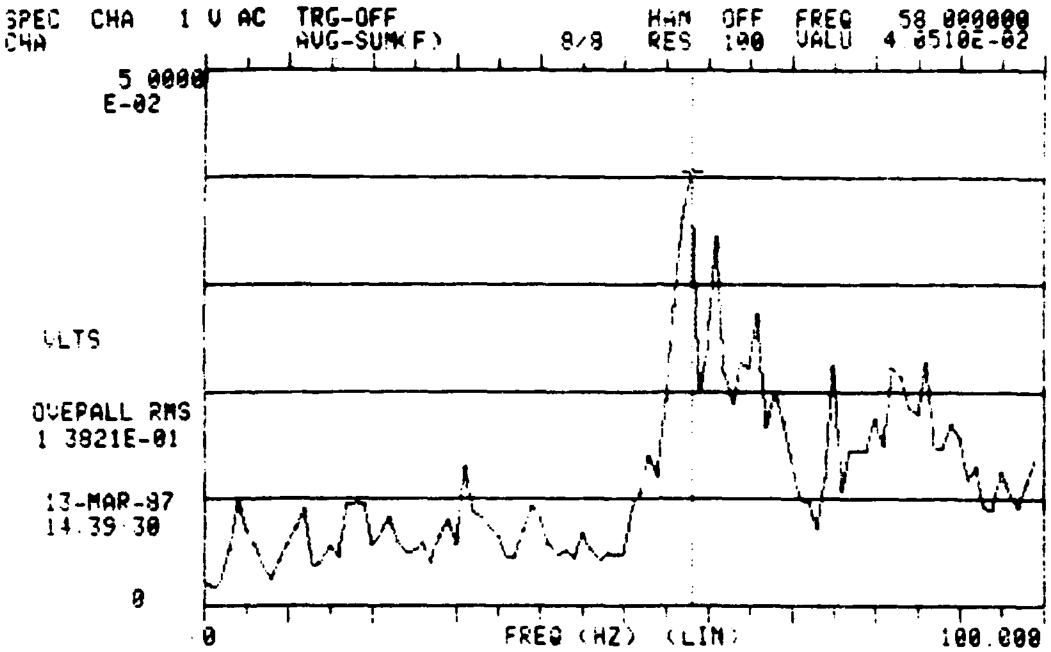
G-34R P#4 at 65.5%



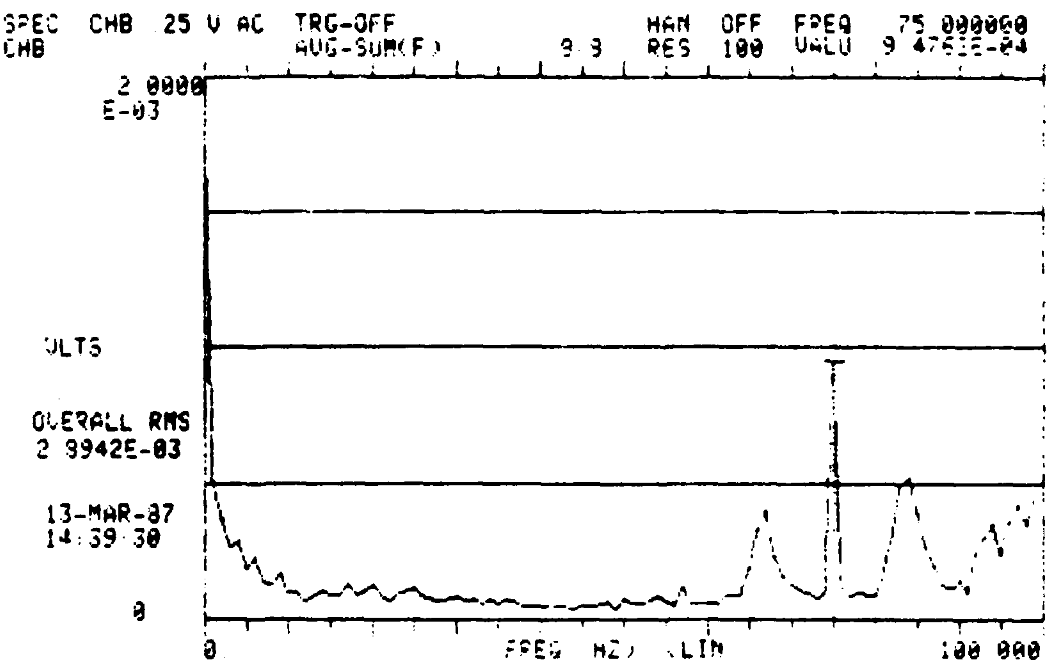
G-34R P#5 at 65.5%



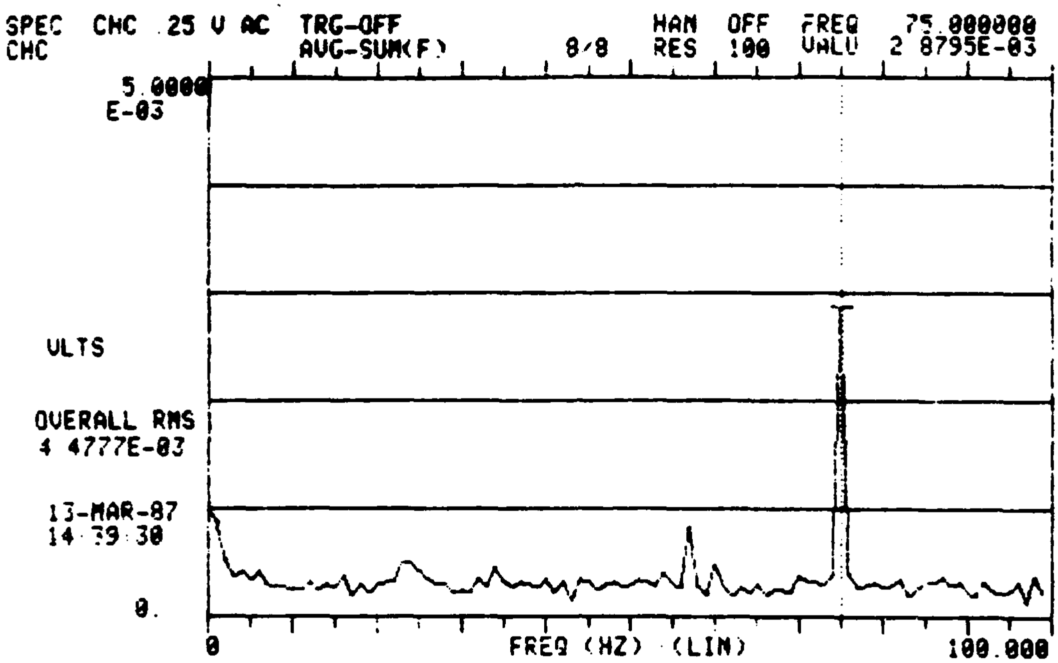
G-tar 3 P#1 at 85%



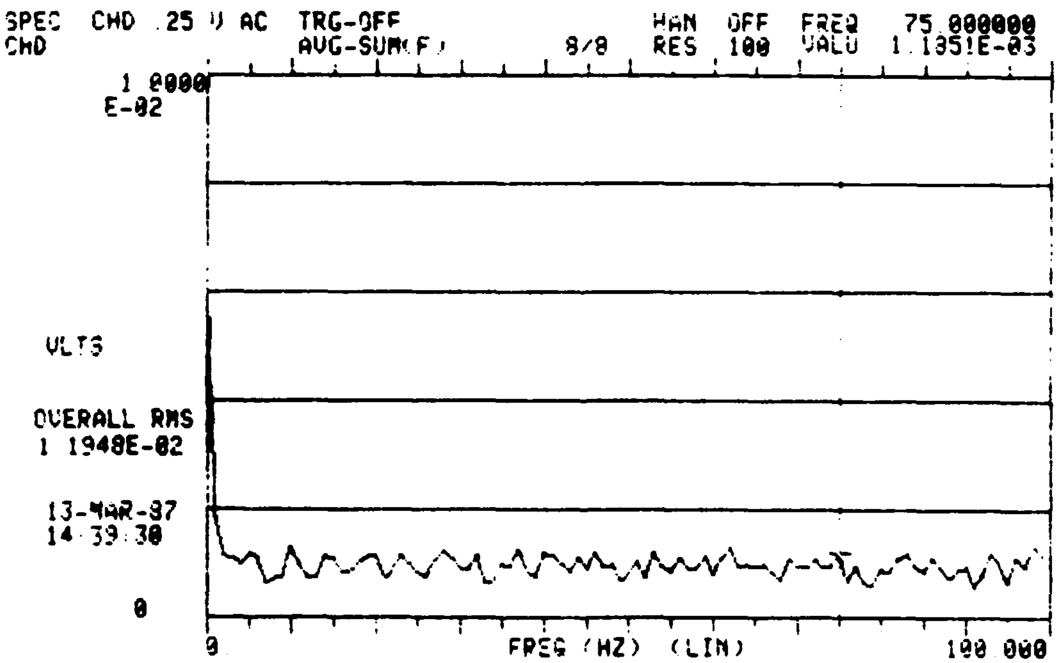
G-tar 3 P#2 at 85%



G-tar 3 P#3 at 85%



G-tar 3 P#5 at 85%



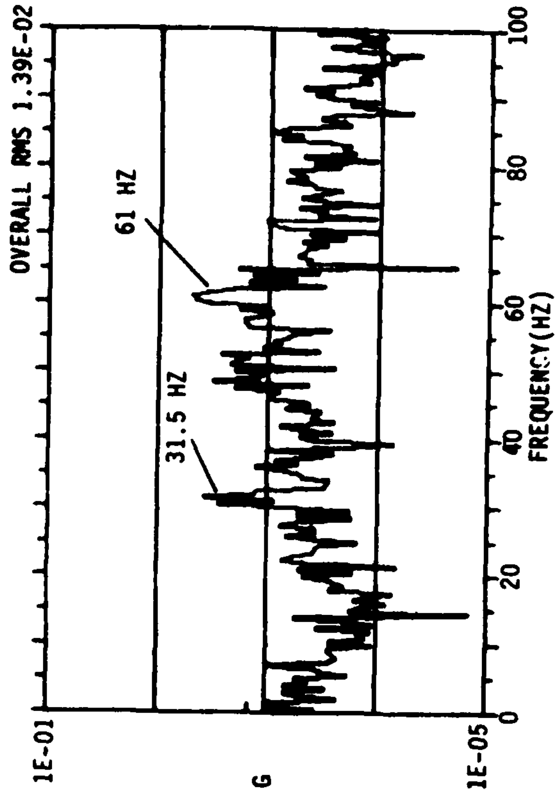
APPENDIX E

DATA ANALYZED FROM ALL FLIGHTS AT McCONNELL AFB

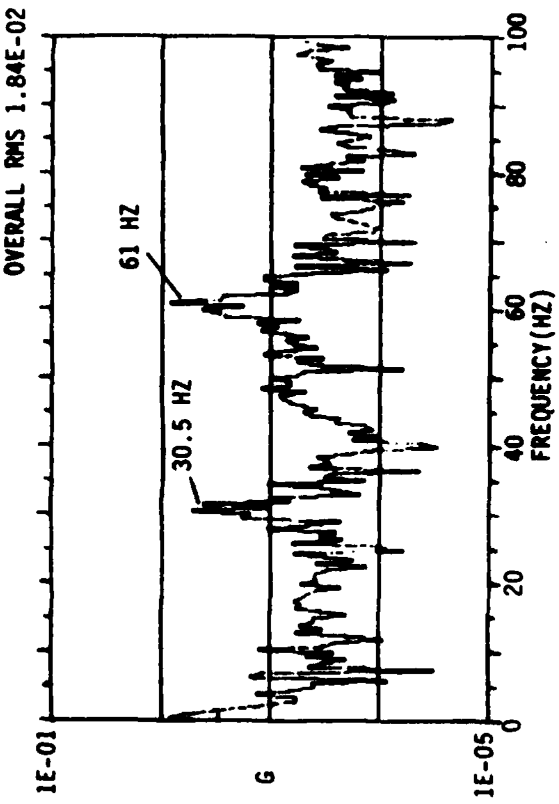
A/C 120

FLIGHT TEST DATA

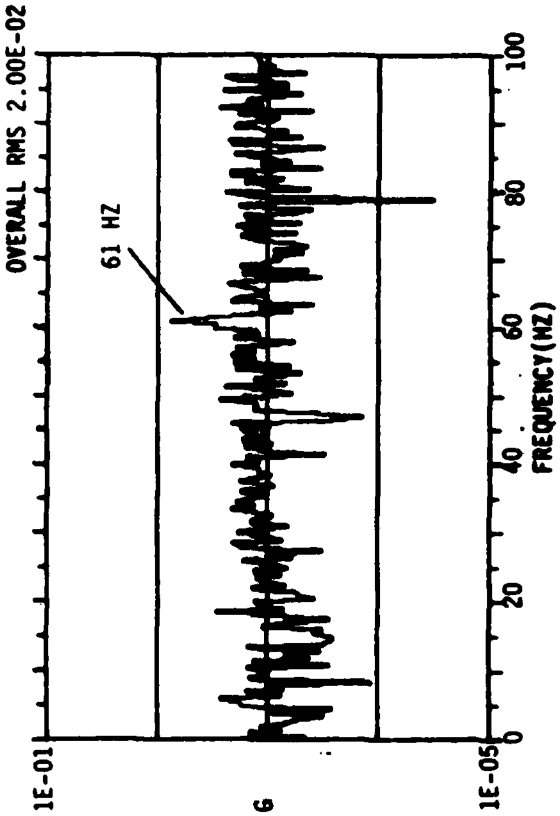
A/C 120 No Rumble



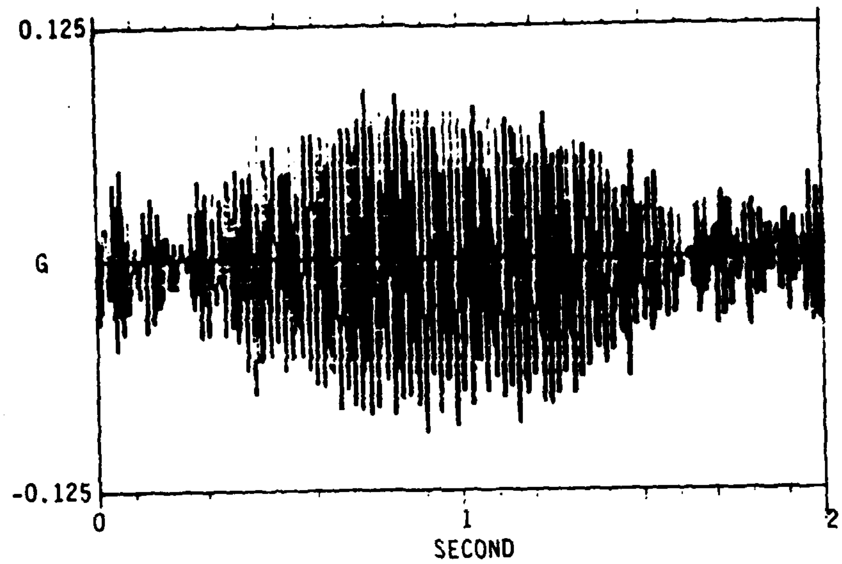
Navigator's Station

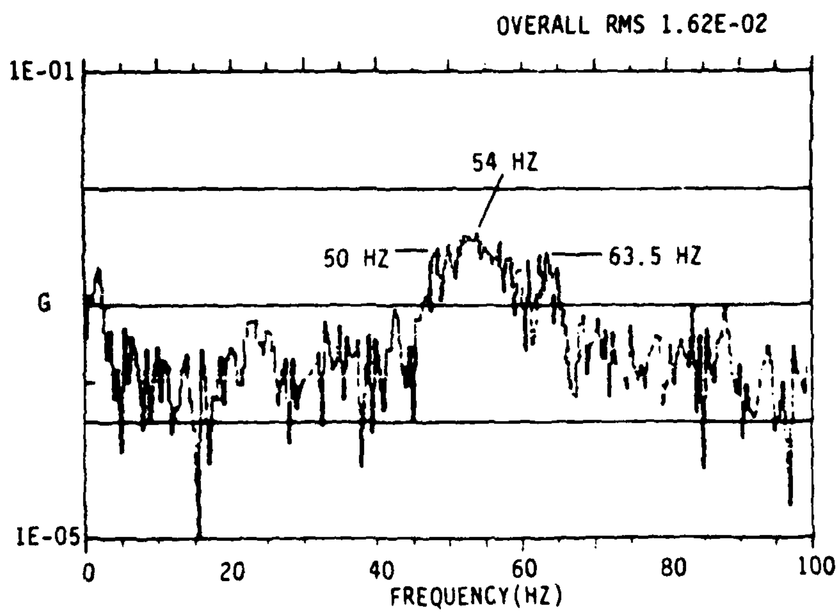


Instrument Housing
Behind Pilot Seat

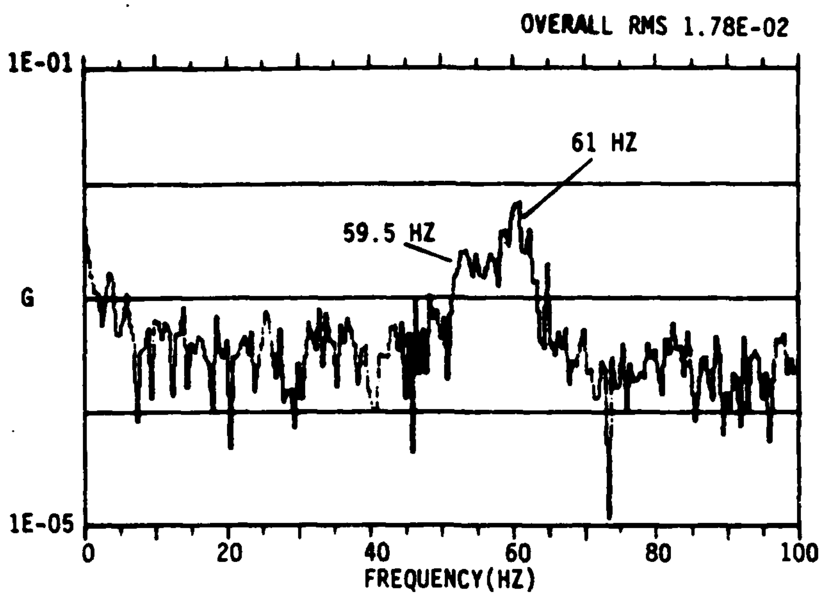


Main Spar Leading Edge

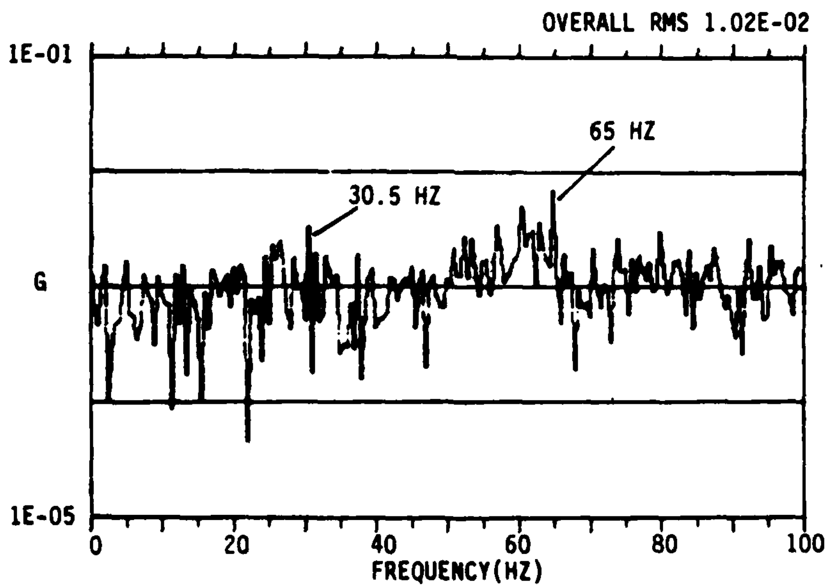




A/C 120 Rumble



Instrument Housing
Behind Pilot's Seat

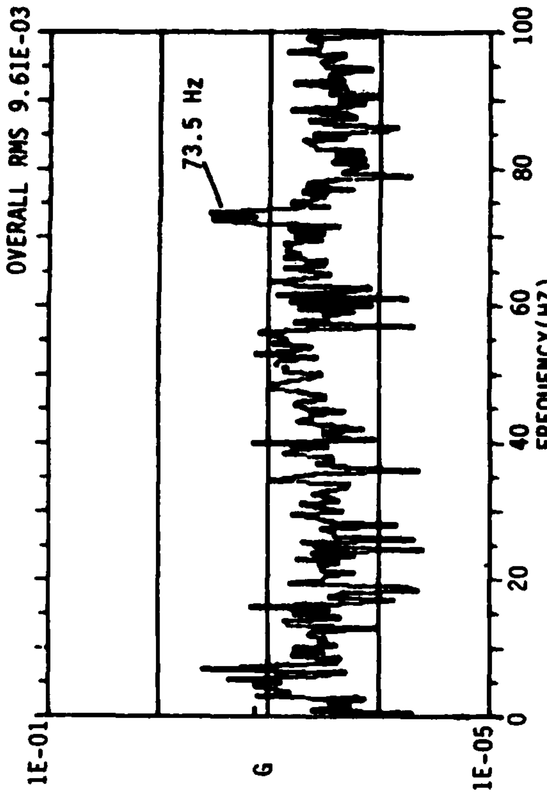


Main Spar Leading Edge

A/C 120 Rumble

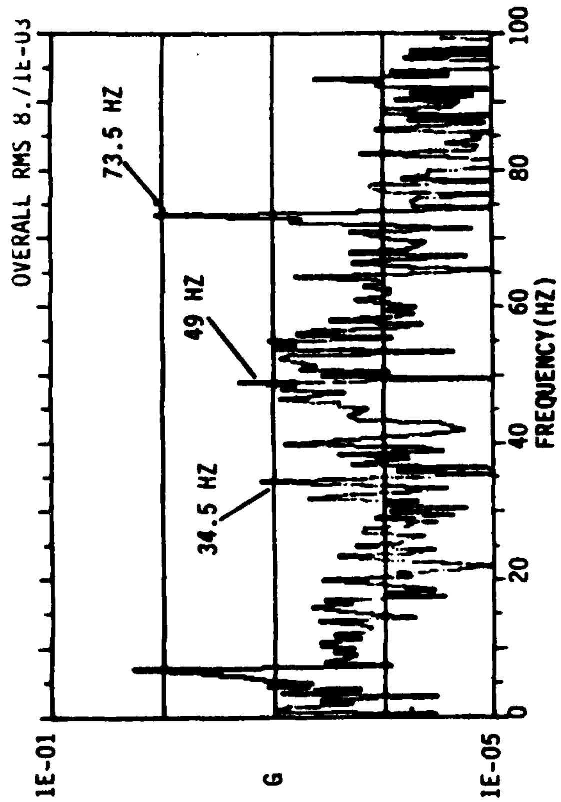
A/C 308

FLIGHT TEST DATA

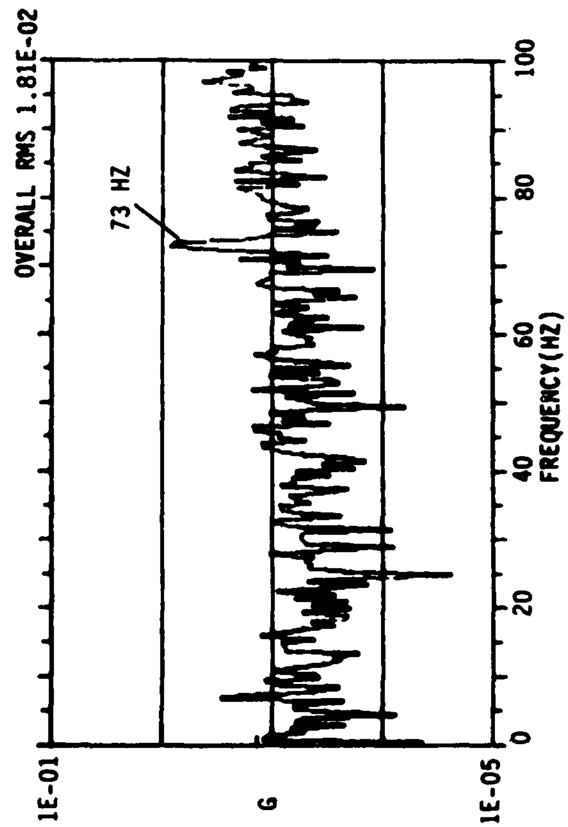


Navigator's Station

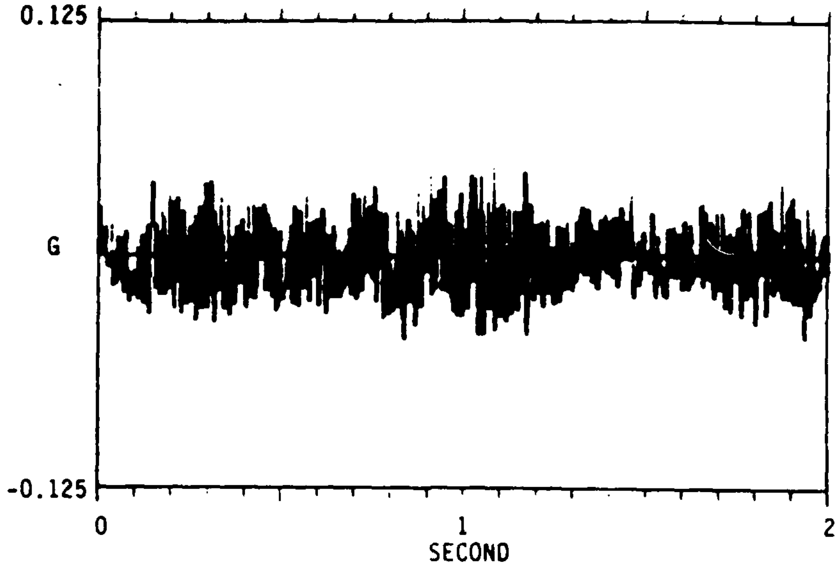
A/C 308 No Rumble

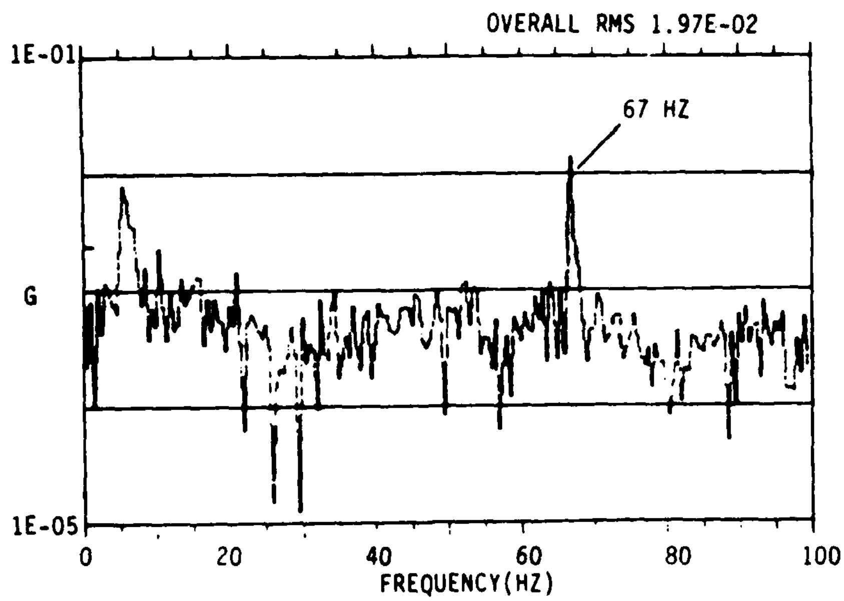


Instrument Housing
Behind Pilot Seat



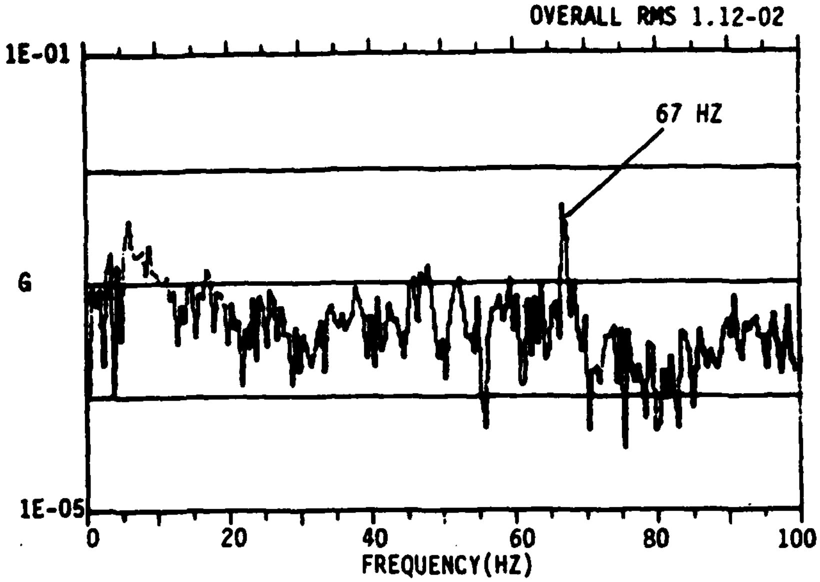
Main Spar Leading Edge



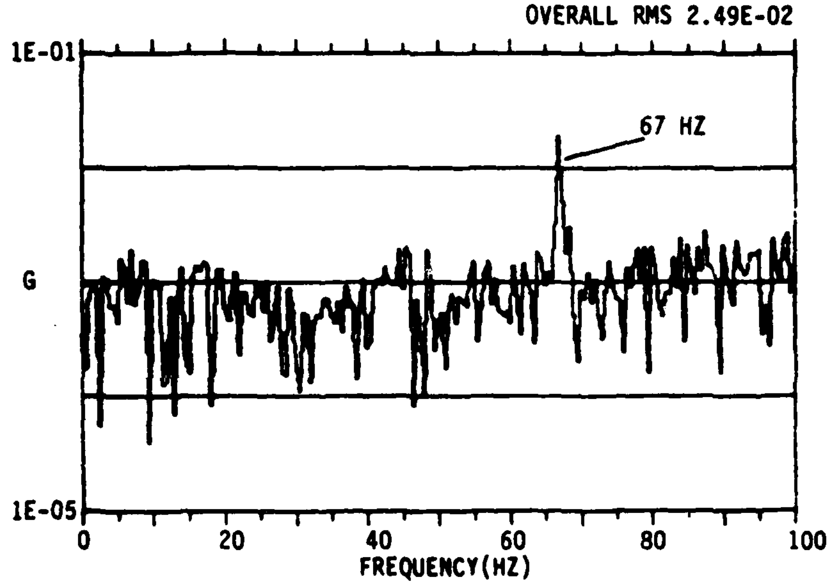


Navigator's Station

A/C 308 Rumble

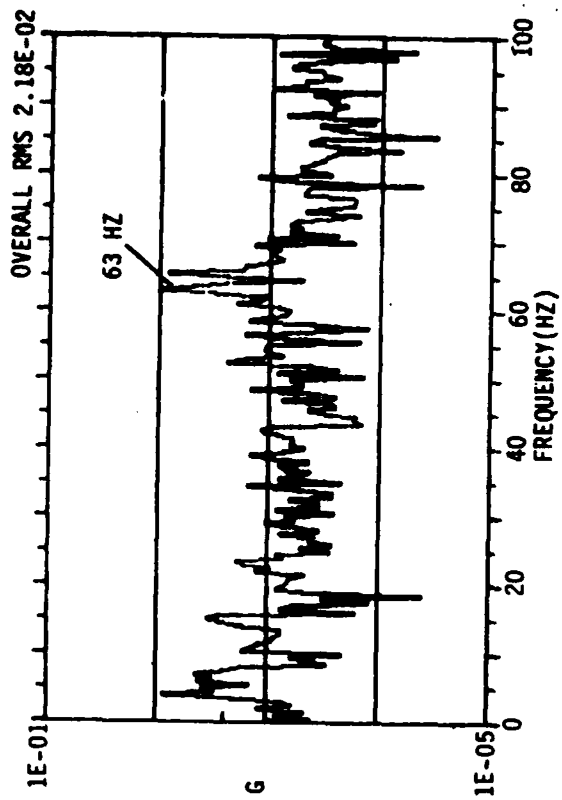


Instrument Housing
Behind Pilot's Seat



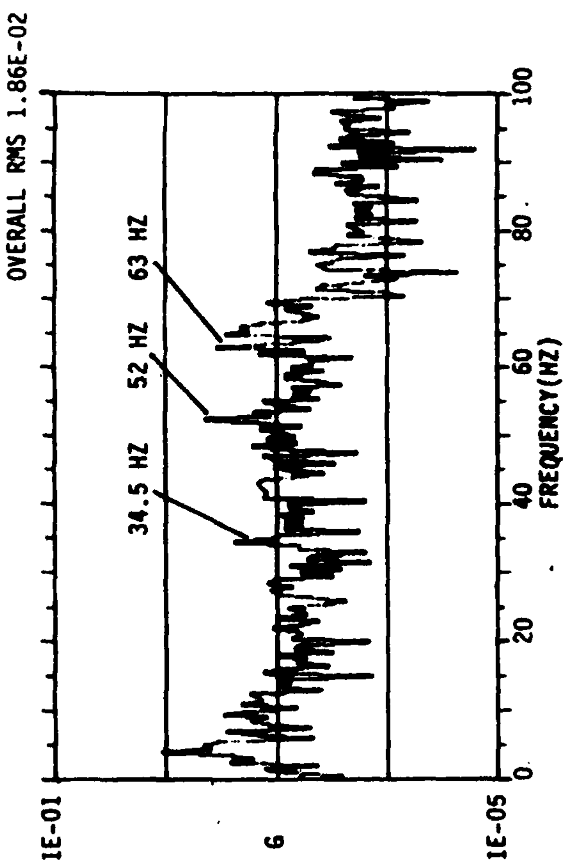
Main Spar Leading Edge

A/C 308 Rumble

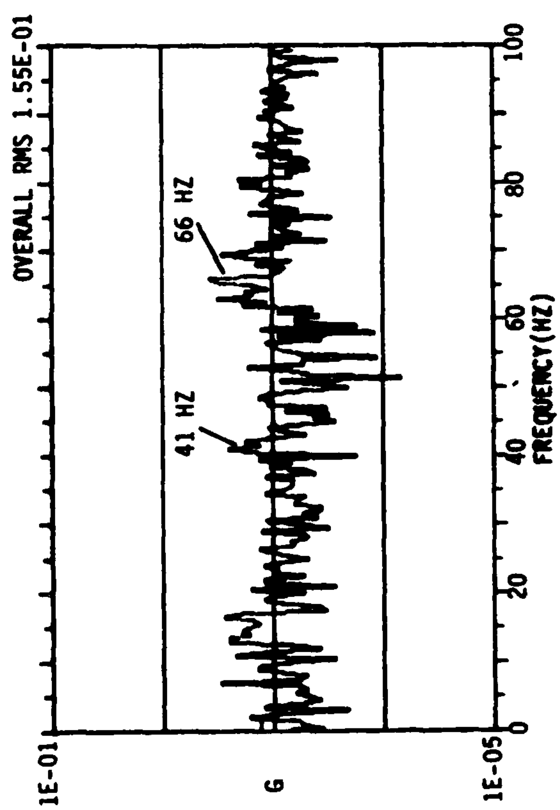


Navigator's Station

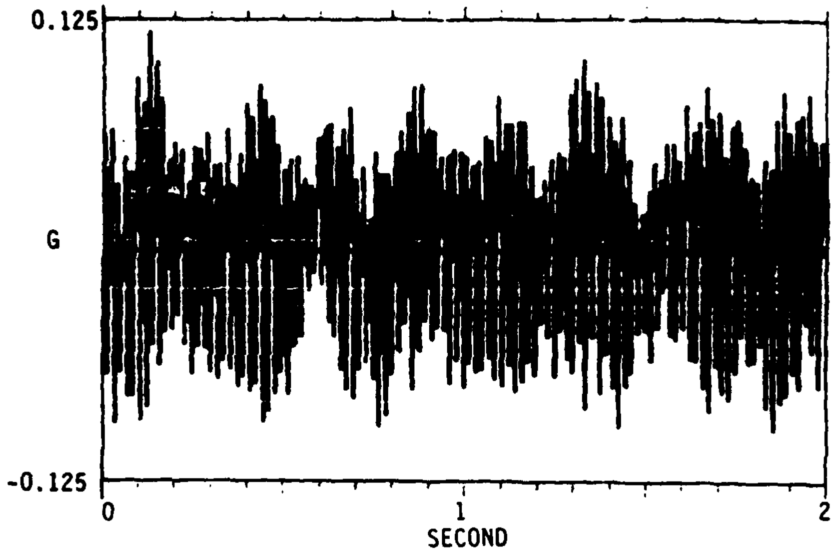
A/C 312 No Rumble

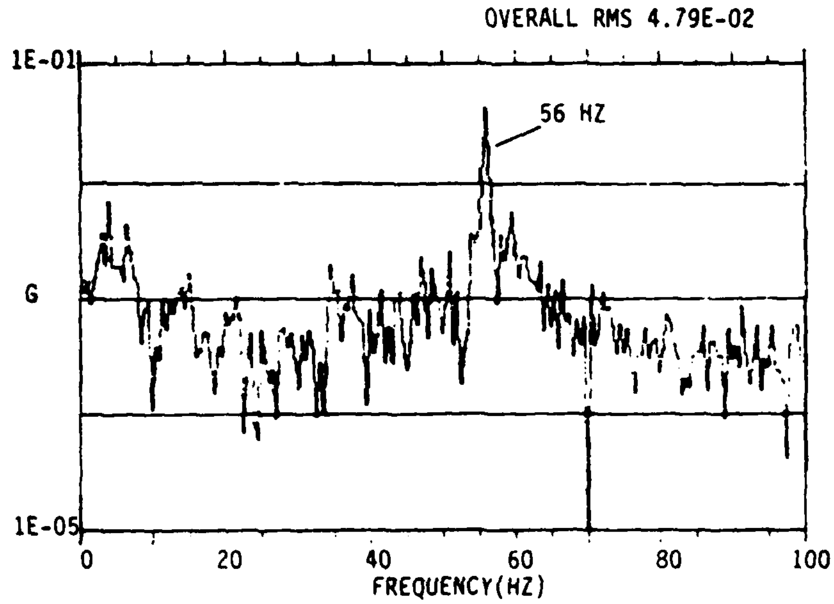


Instrument Housing
Behind Pilot Seat



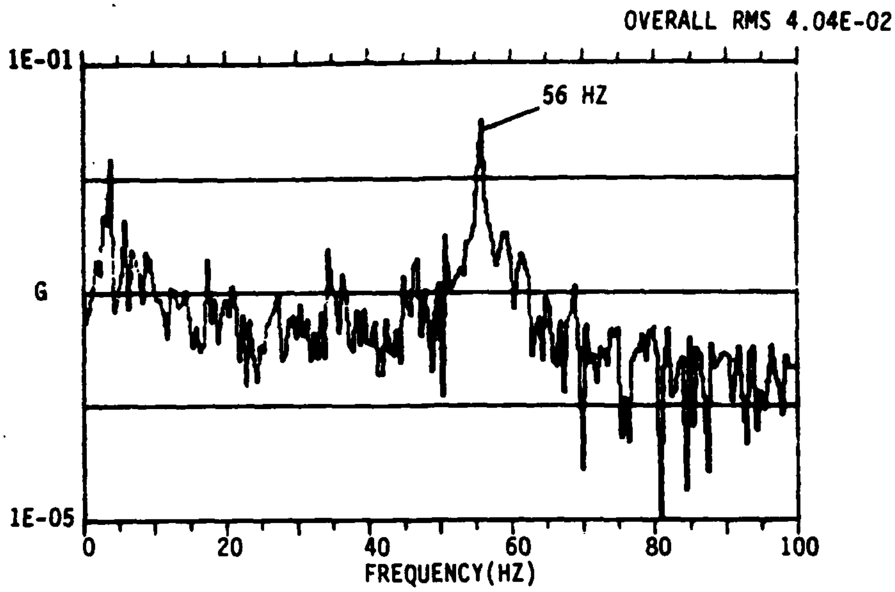
Main Spar Leading Edge



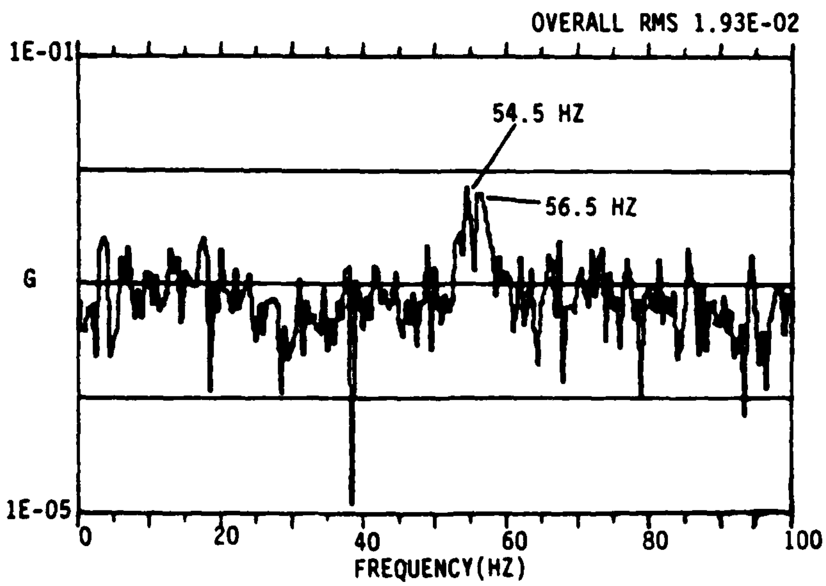


Navigator's Station

A/C 312 Rumble

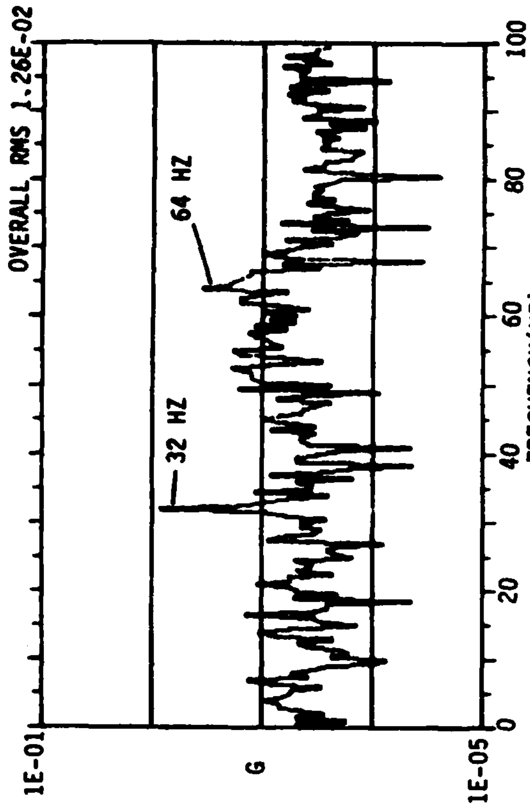


Instrument Housing
Behind Pilot's Seat



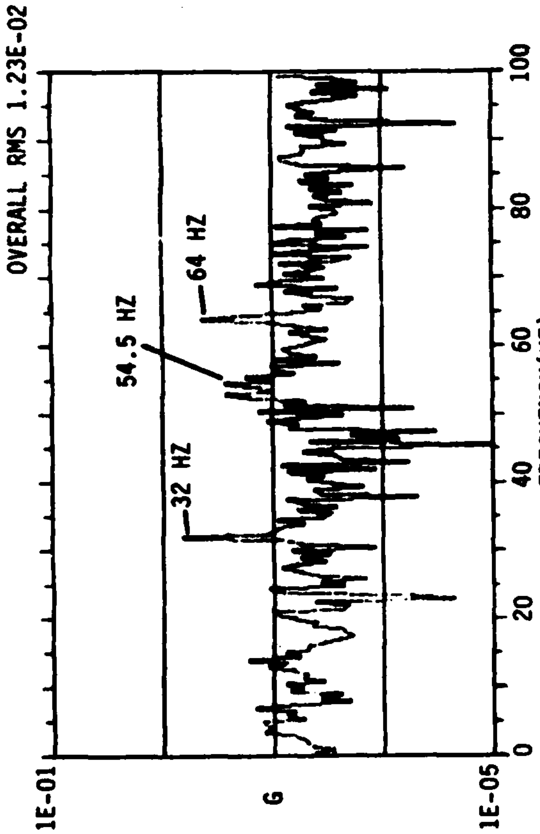
Main Spar Leading Edge

A/C 312 Rumble

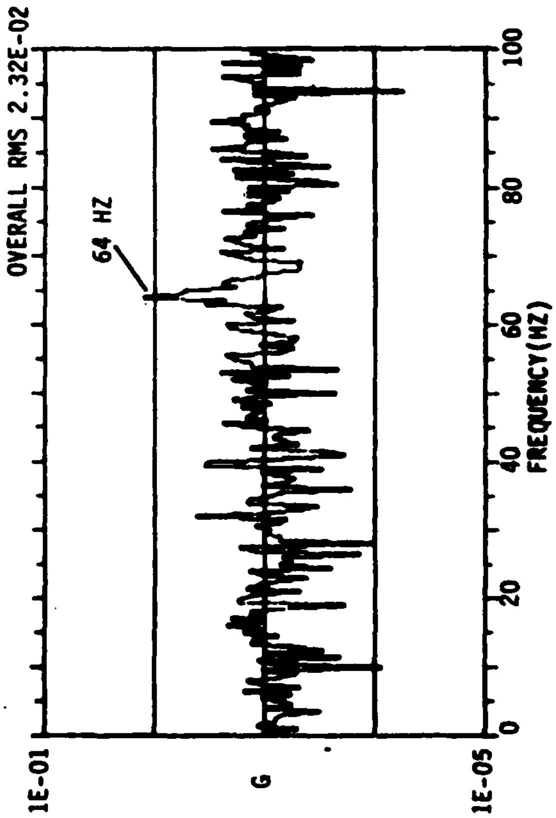


Navigator's Station

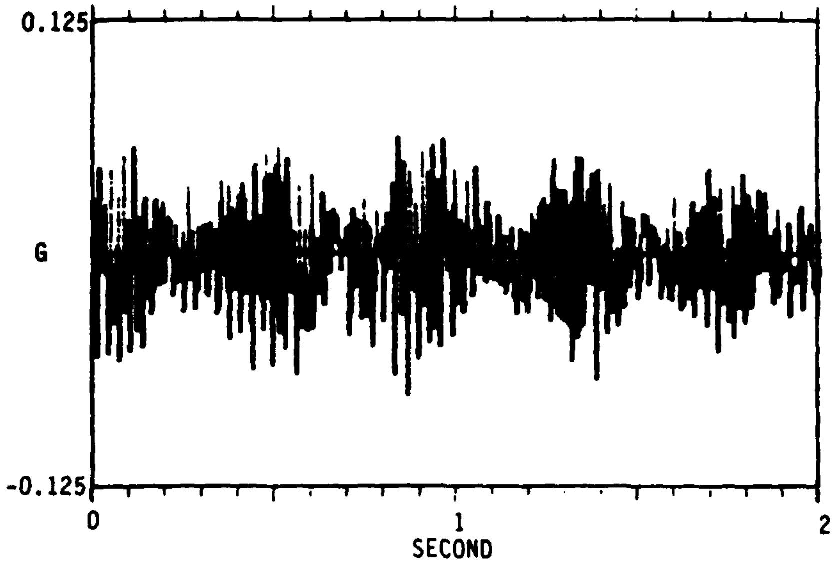
A/C 482 No Rumble

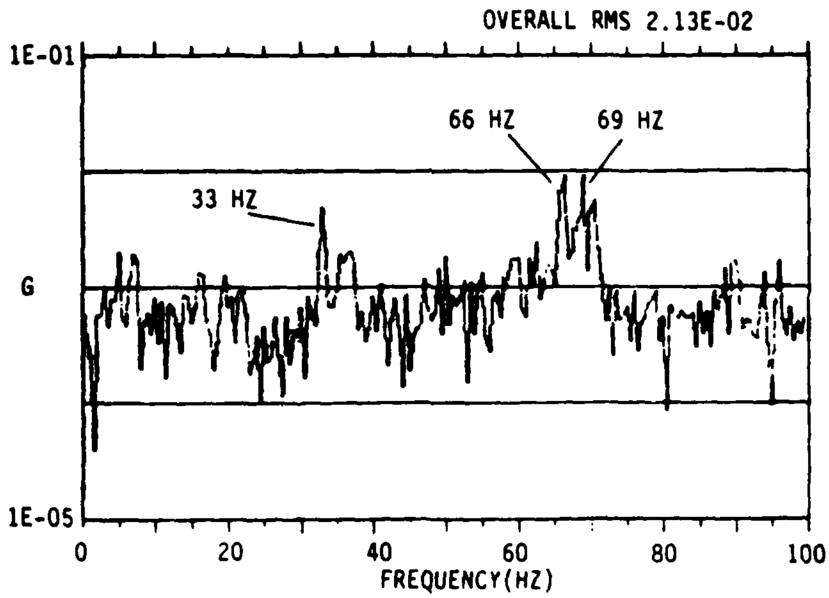


Instrument Housing
Behind Pilot Seat



Main Spar Leading Edge





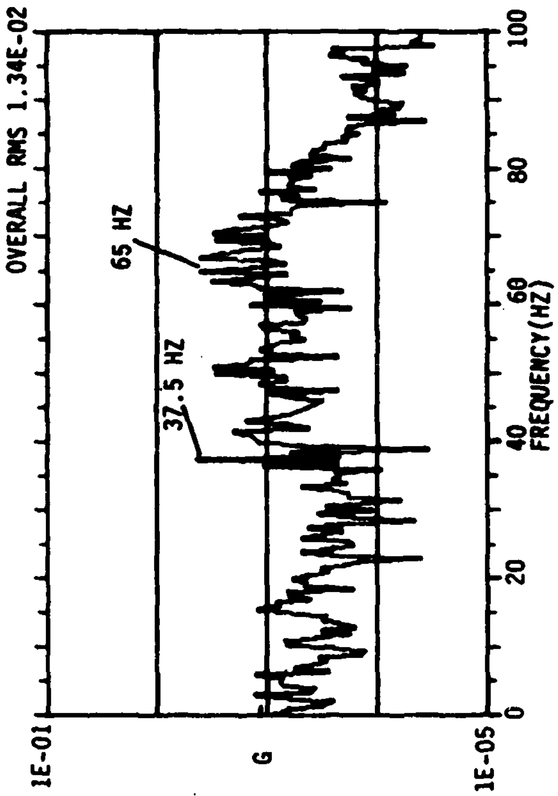
Navigator's Station

A/C 482 Rumble

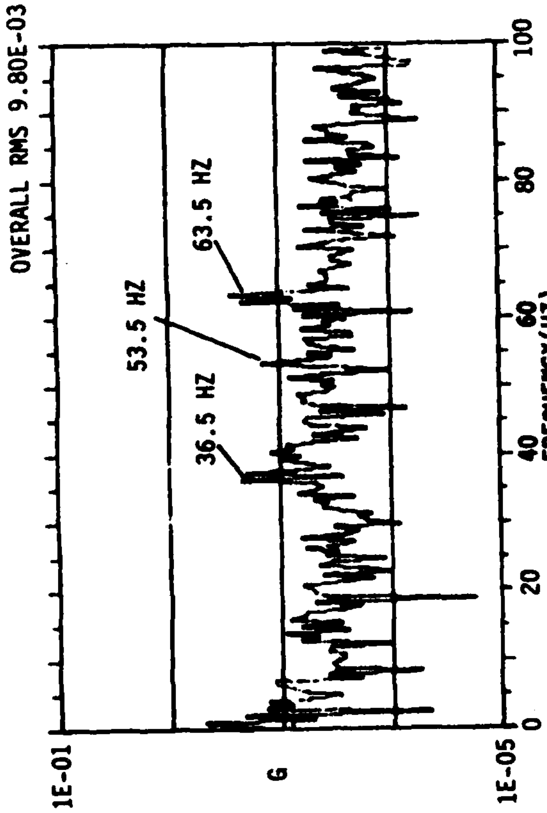
A/C 502

FLIGHT TEST DATA

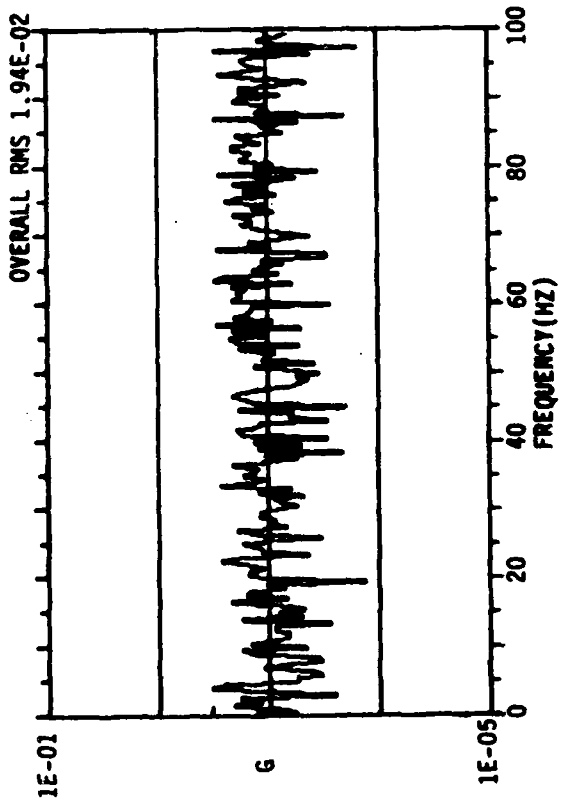
A/C 502 No Rumble



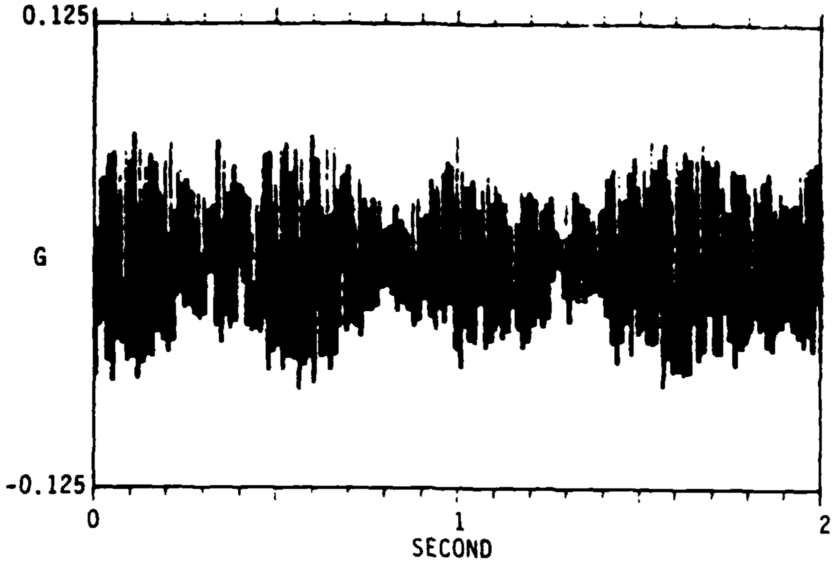
Navigator's Station

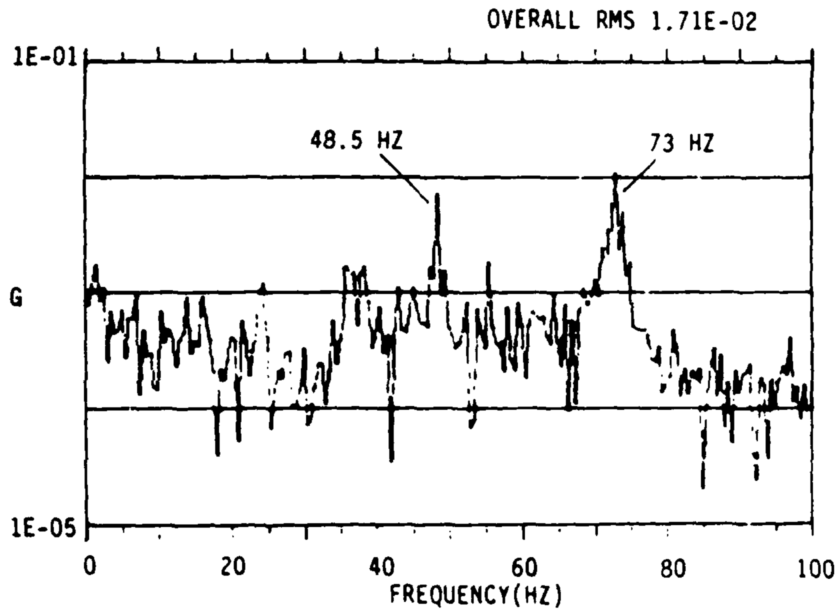


Instrument Housing
Behind Pilot Seat



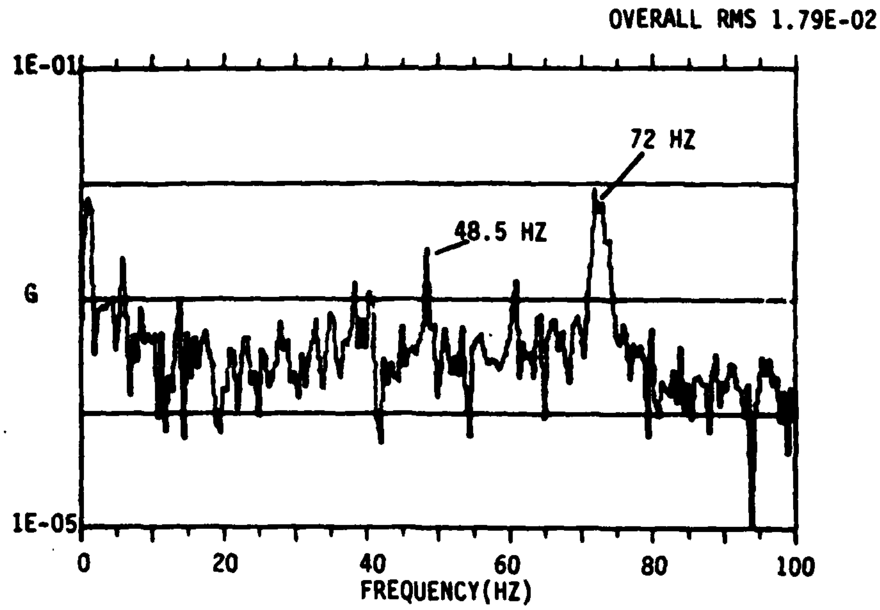
Main Spar Leading Edge



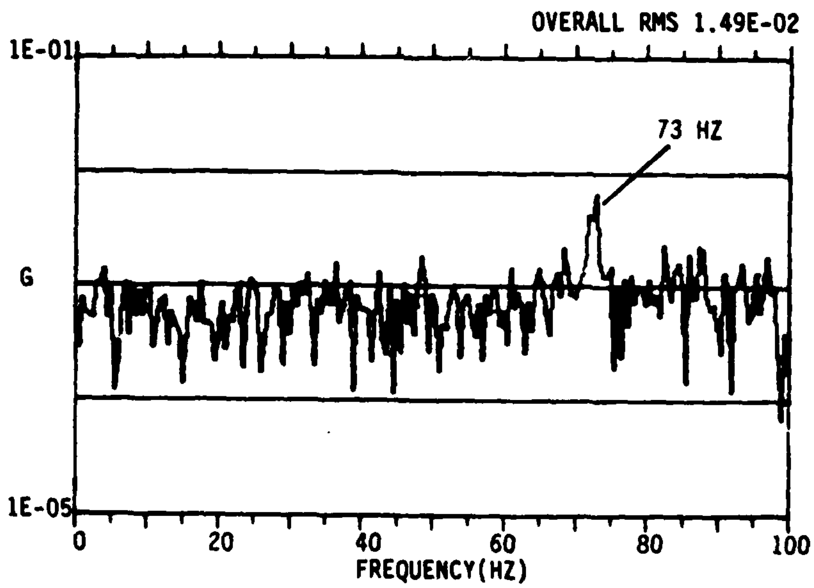


Navigator's Station

A/C 502 Rumble



Instrument Housing
Behind Pilot's Seat

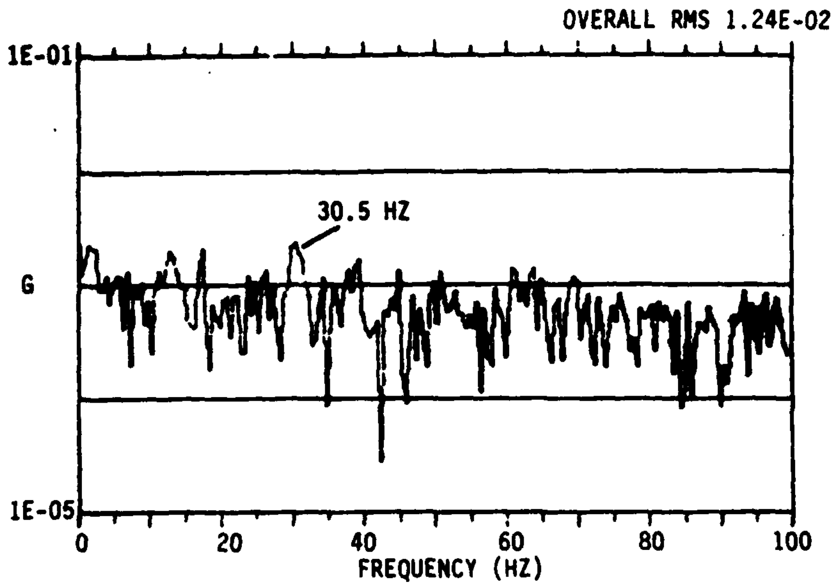


Main Spar Leading Edge

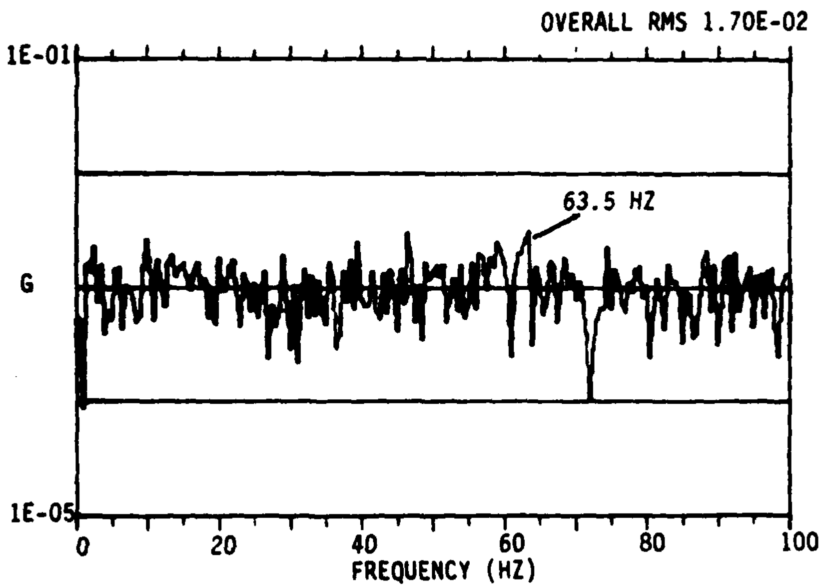
A/C 502 Rumble

A/C 306

FLIGHT TEST DATA

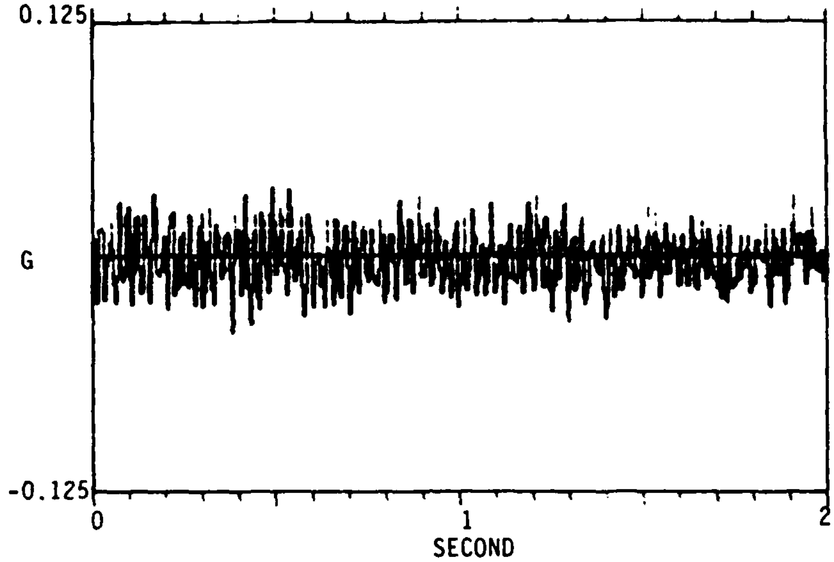


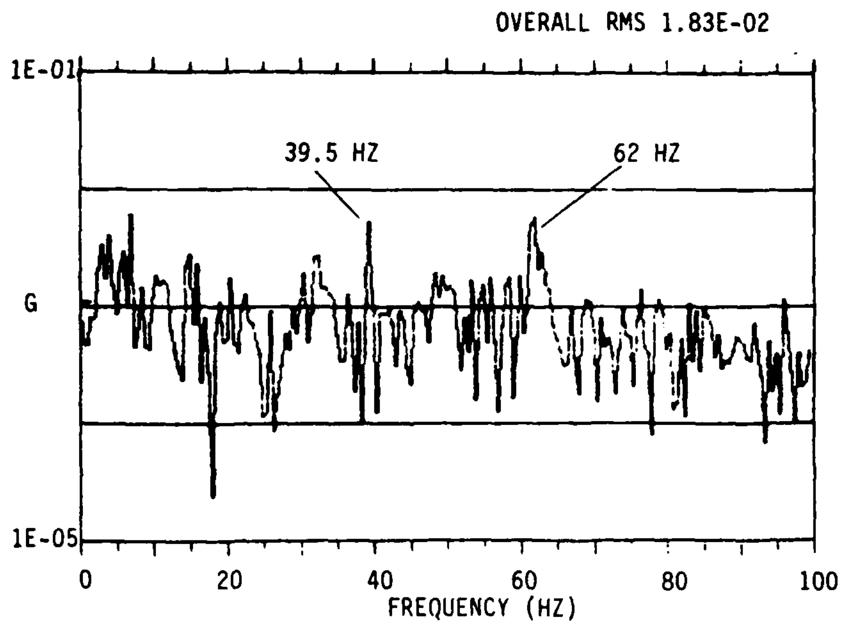
Instrument Housing
Behind Pilot's Seat



Main Spar Leading Edge

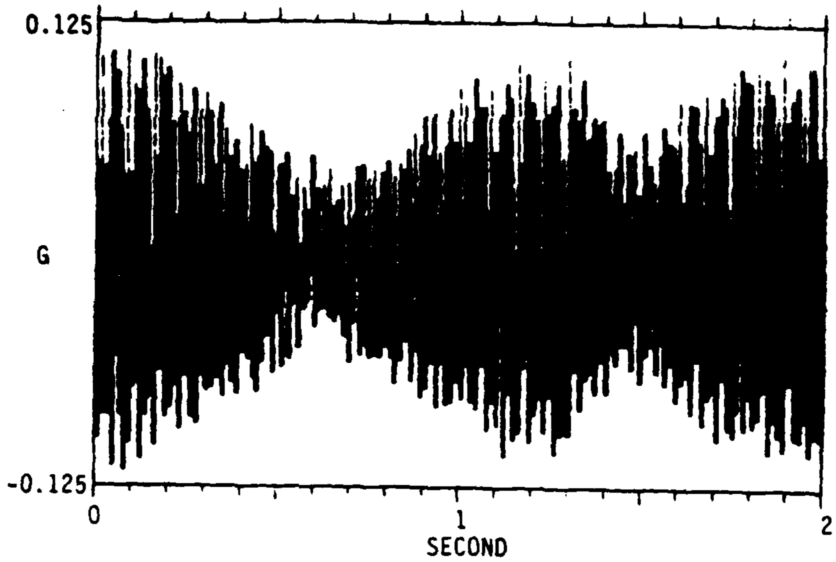
A/C 306 No Rumble

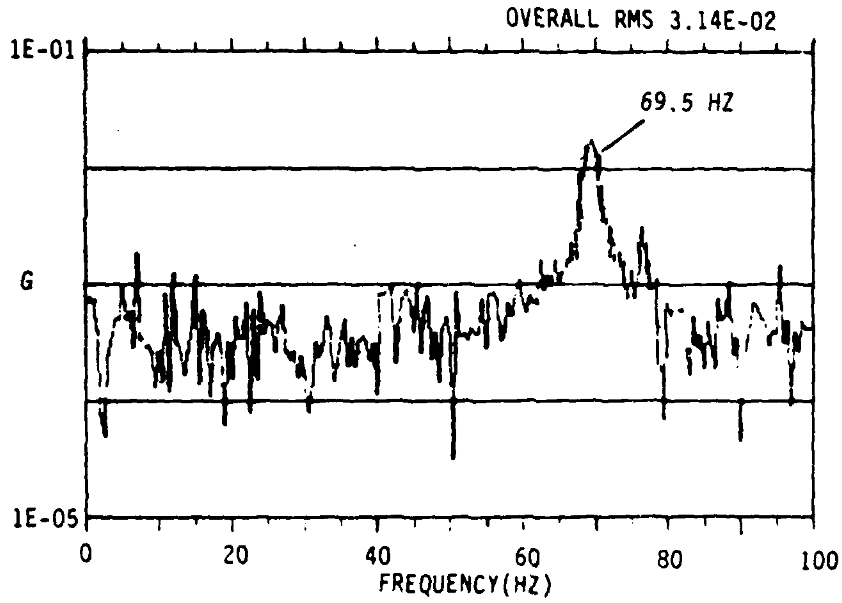




Navigator's Station

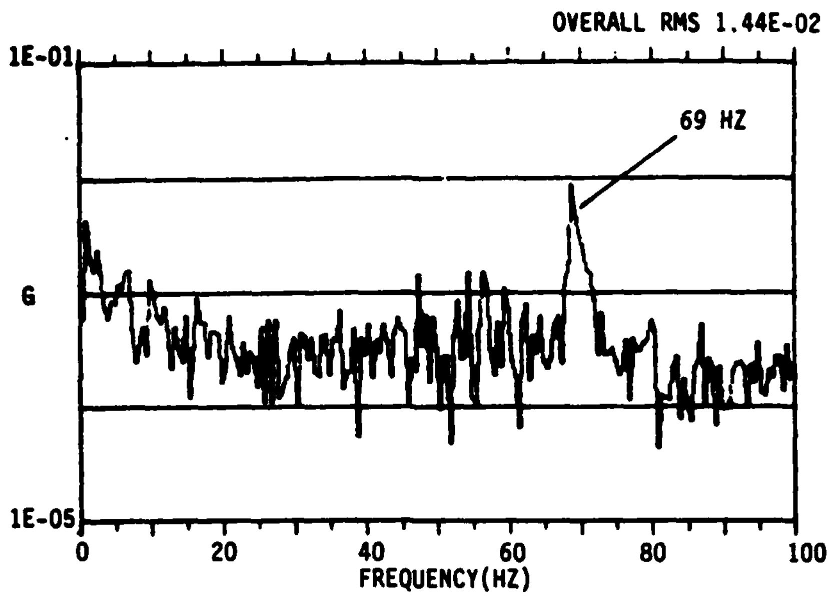
A/C 306 No Rumble



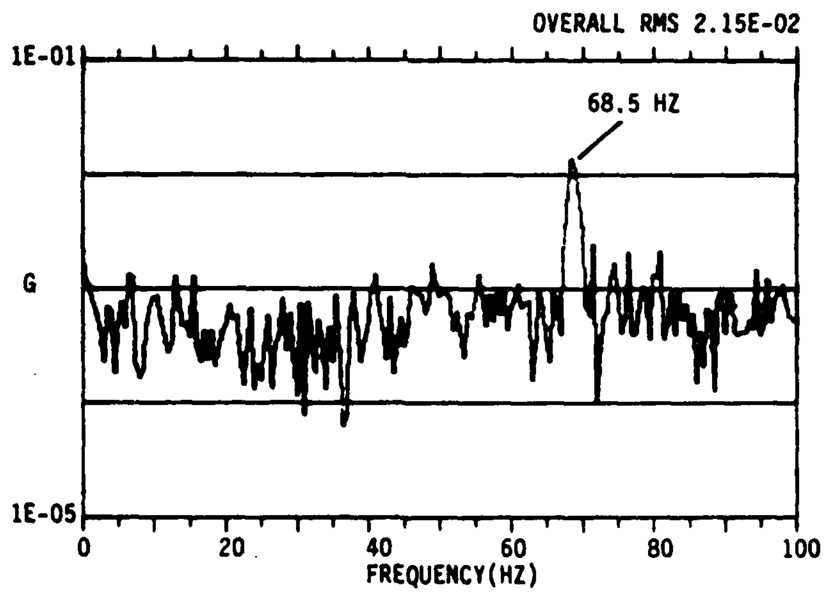


Navigator's Station

A/C 306 Rumble A

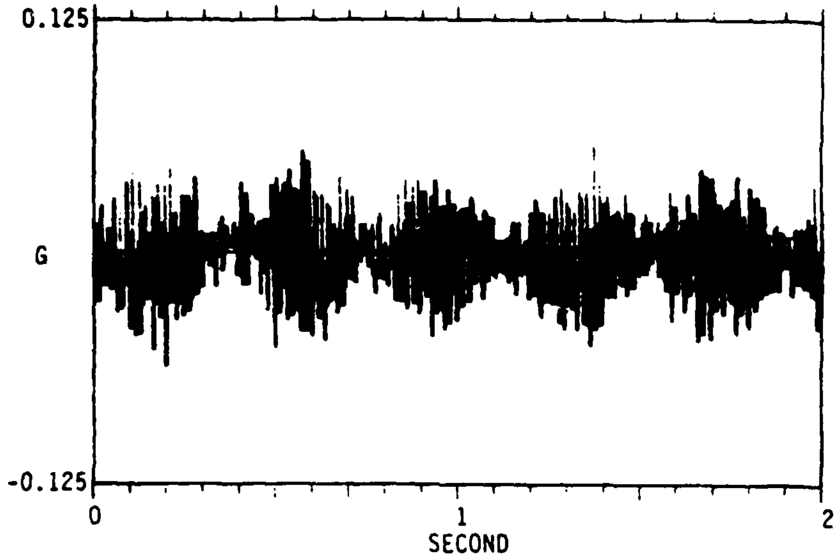


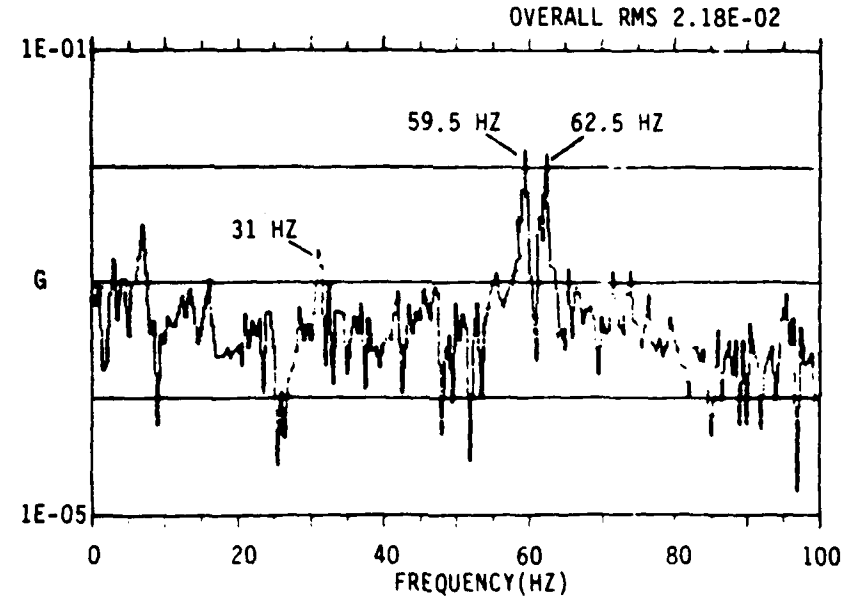
Instrument Housing
Behind Pilot's Seat



Main Spar Leading Edge

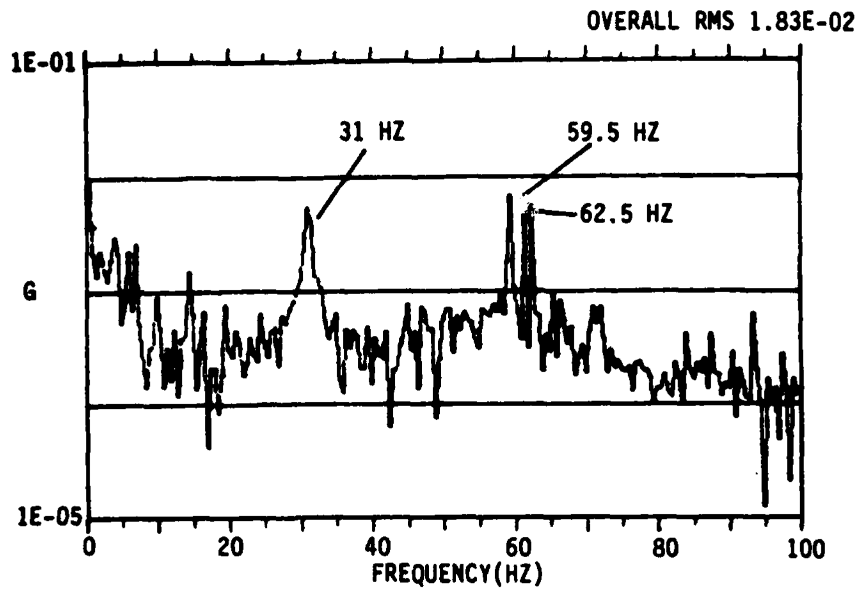
A/C 306 Rumble A



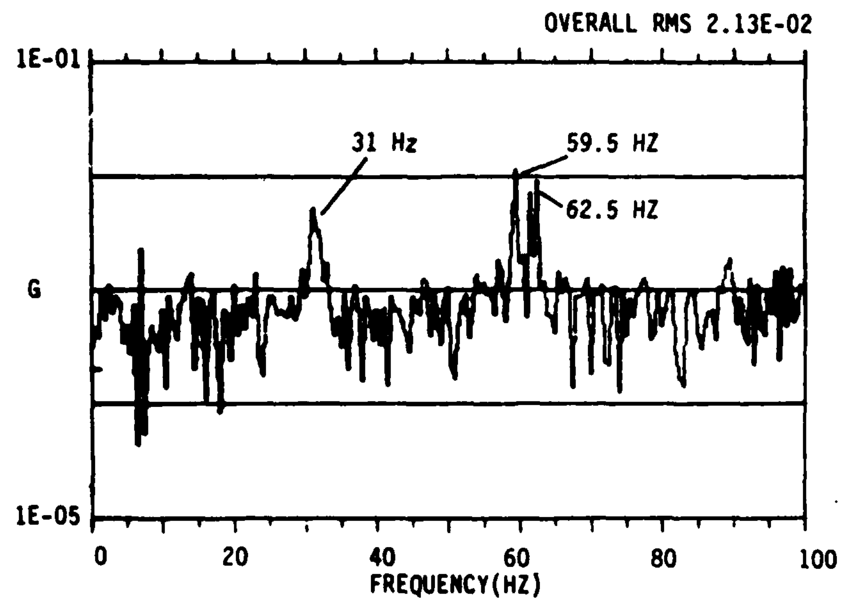


Navigator's Station

A/C 306 Rumble B

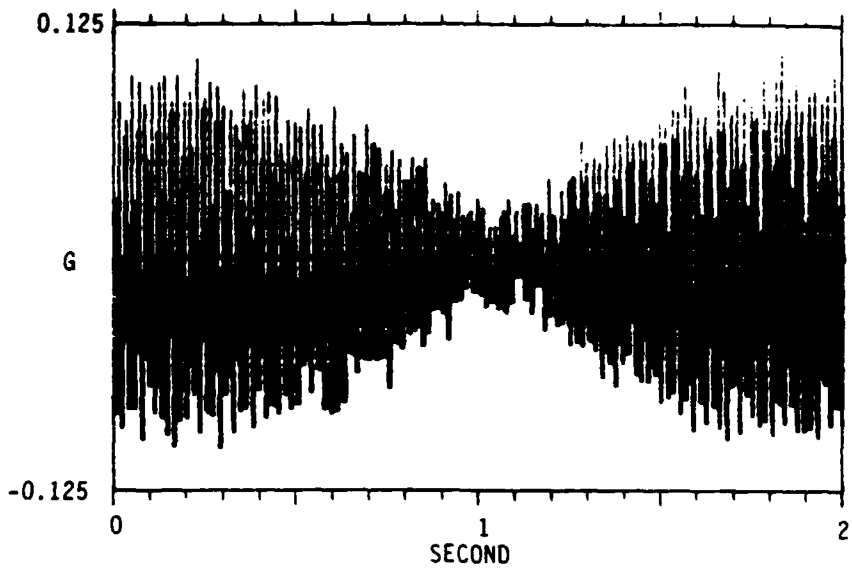


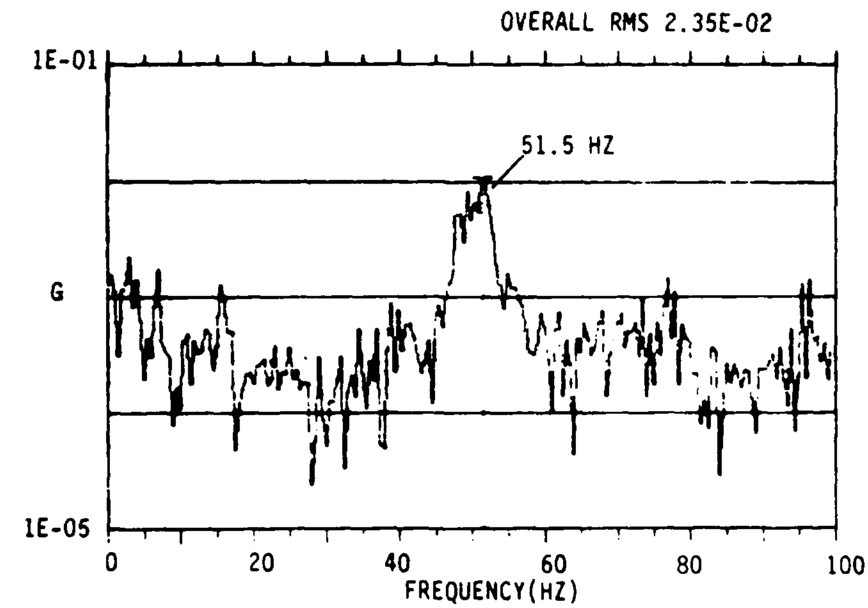
Instrument Hou ing
Behind Pilot's Seat



Main Spar Leading Edge

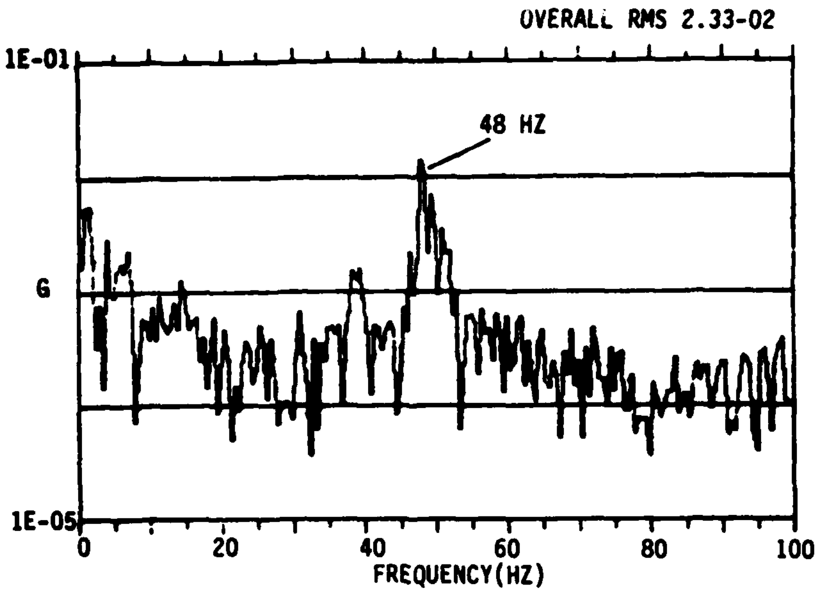
A/C 306 Rumble B



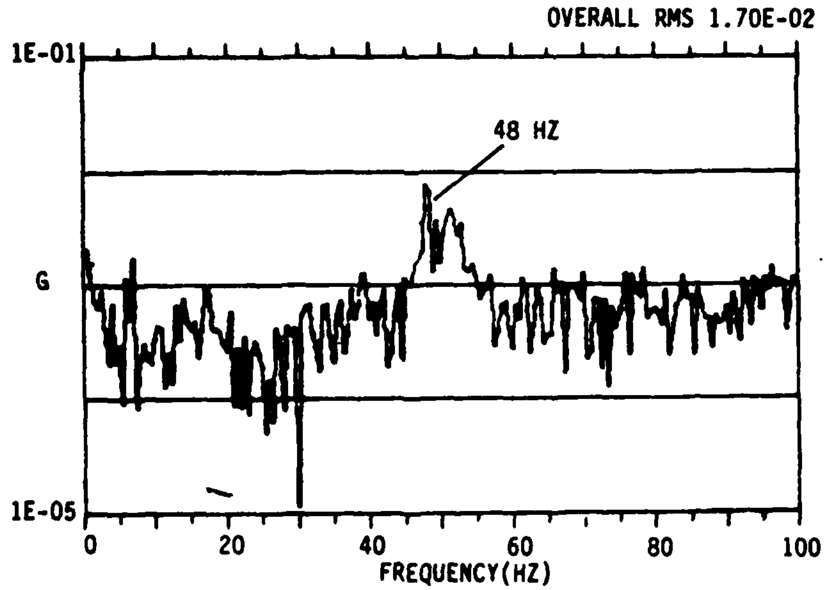


Navigator's Station

A/C 306 Rumble C

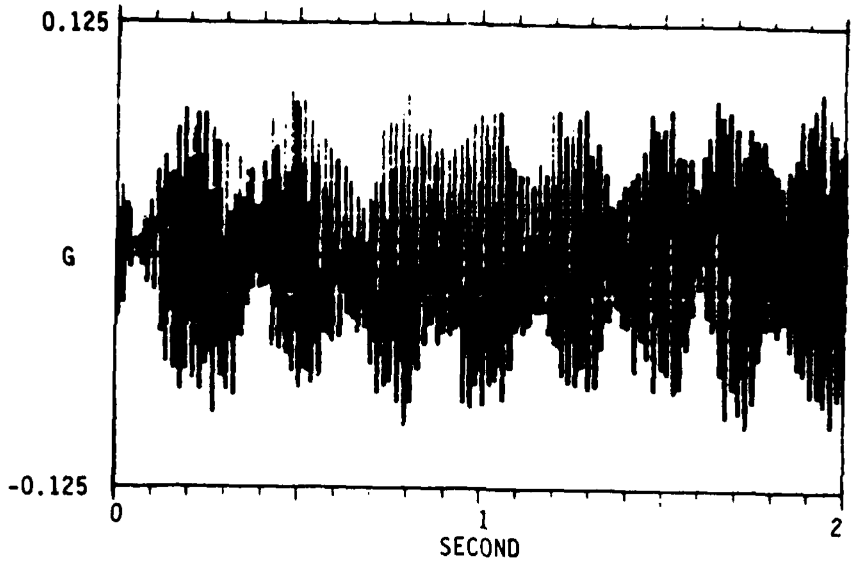


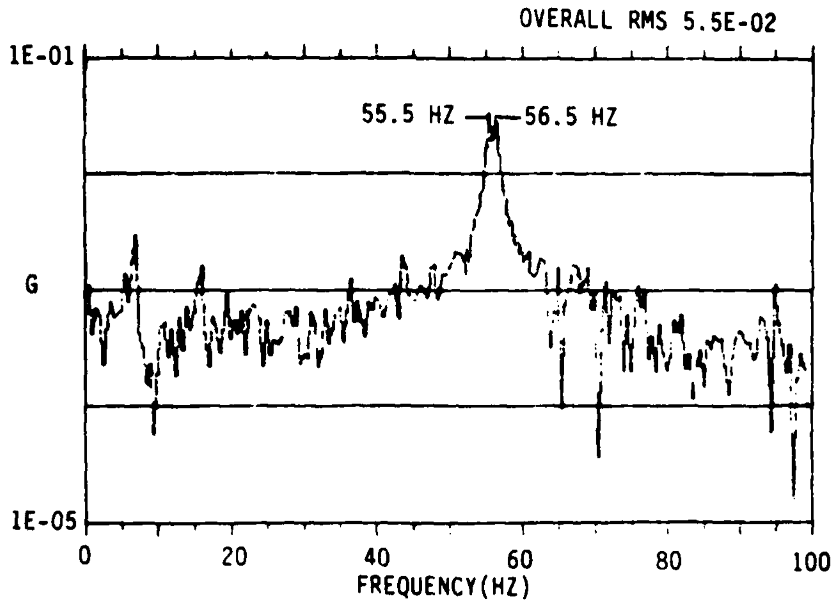
Instrument Housing
Behind Pilot's Seat



Main Spar Leading Edge

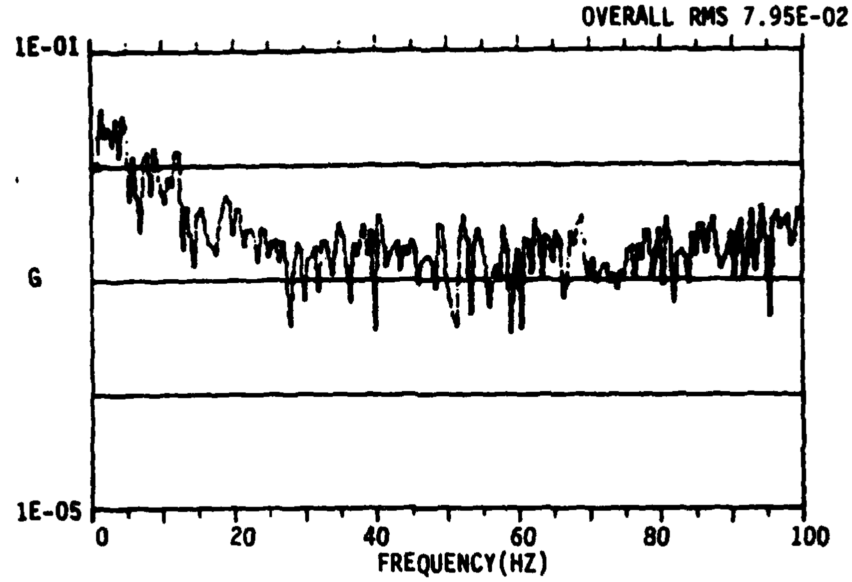
A/C 306 Rumble C



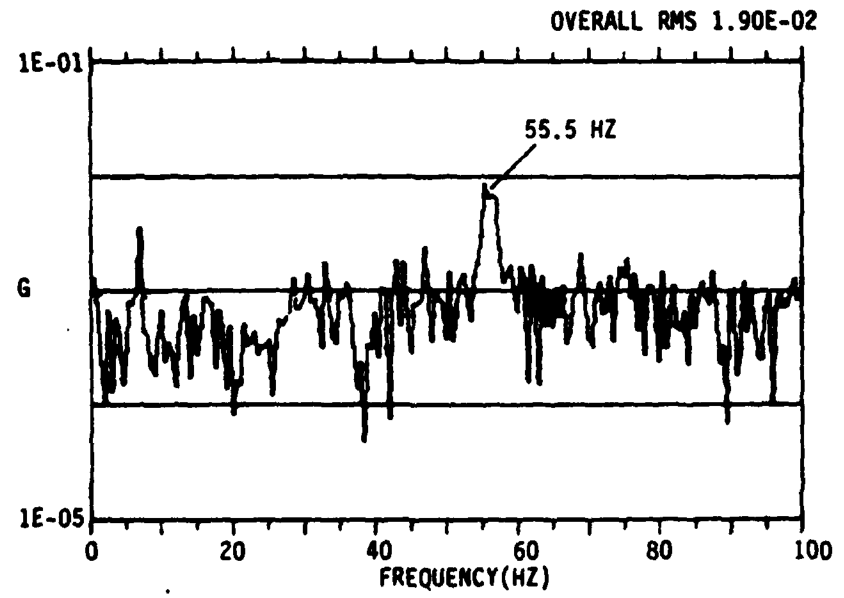


Navigator's Station

A/C 306 Rumble D

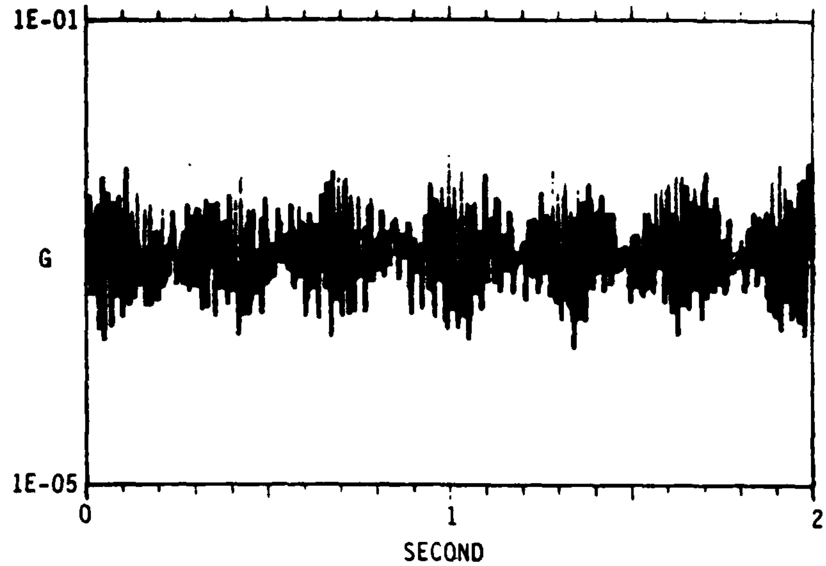


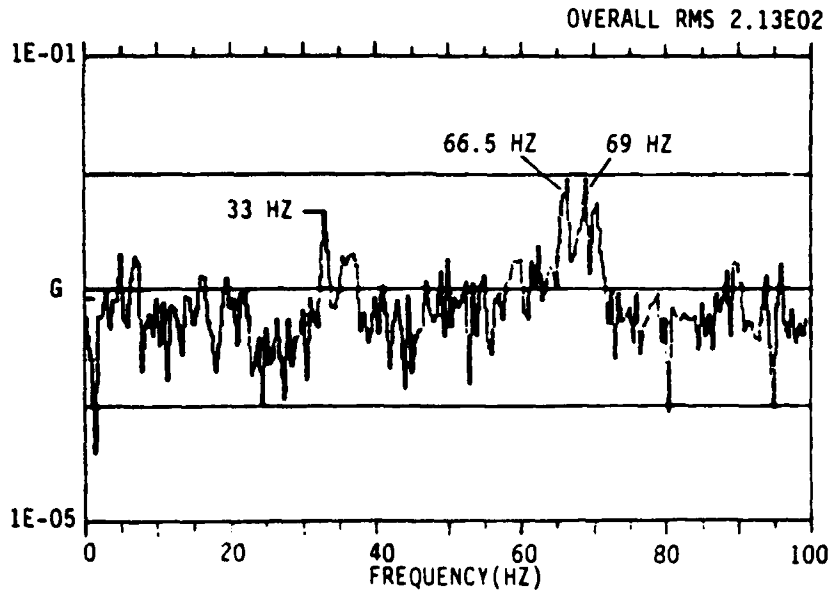
Instrument Housing
Behind Pilot's Seat



Main Spar Leading Edge

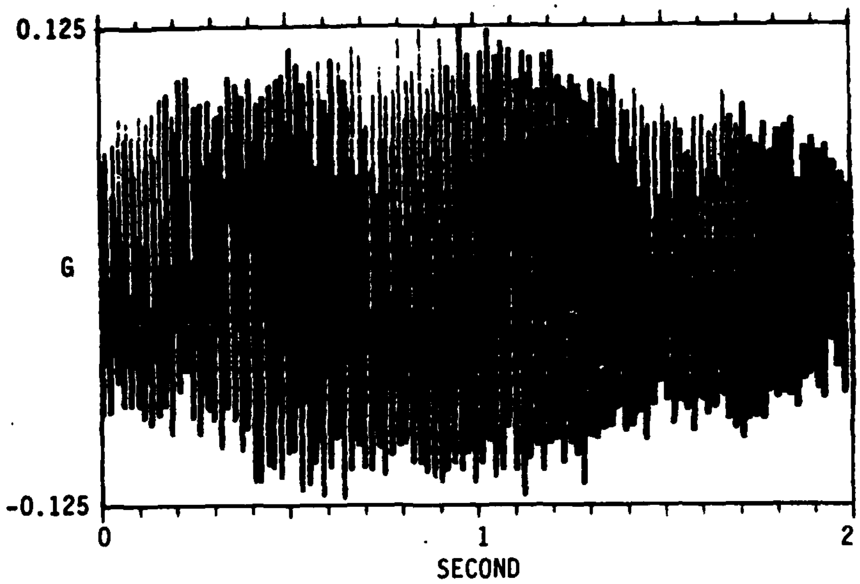
A/C 306 Rumble D

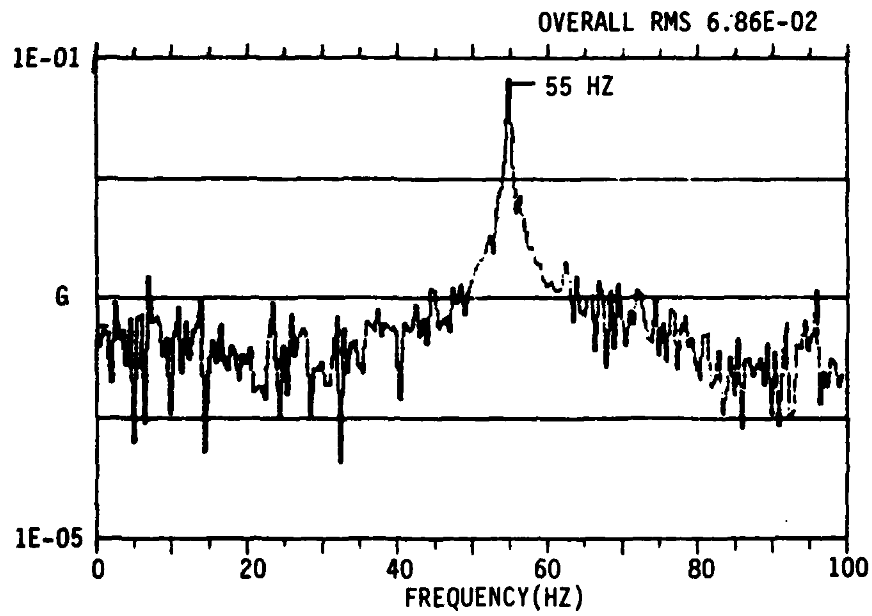




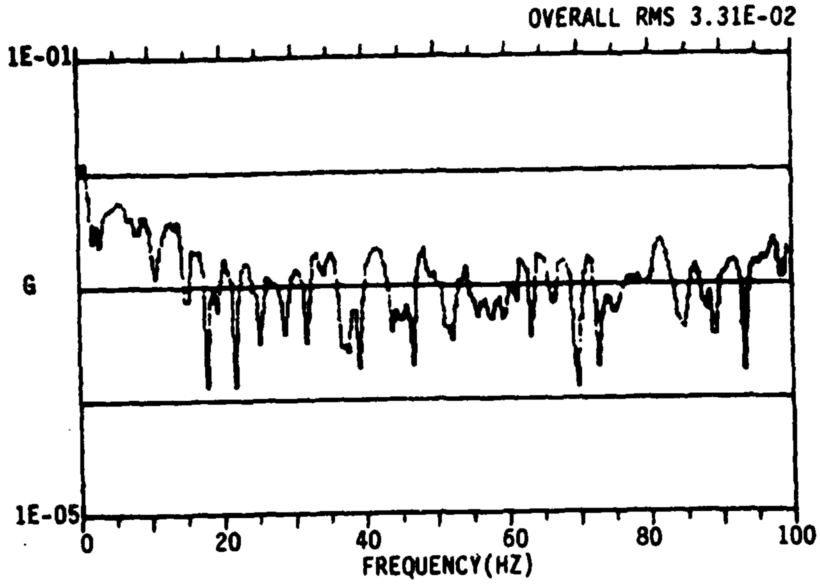
Navigator's Station

A/C 306 Rumble E

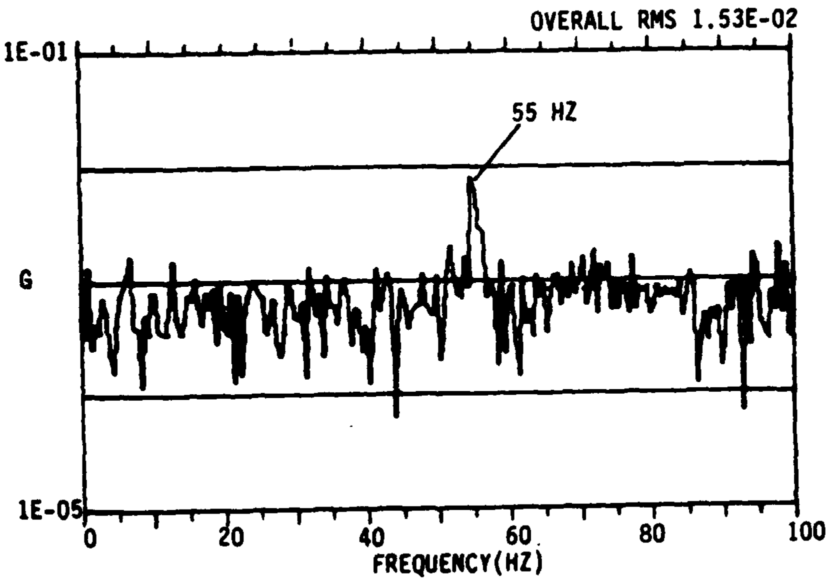




A/C 306 Rumble F



Instrument Housing
Behind Pilot's Seat



Main Spar Leading Edge

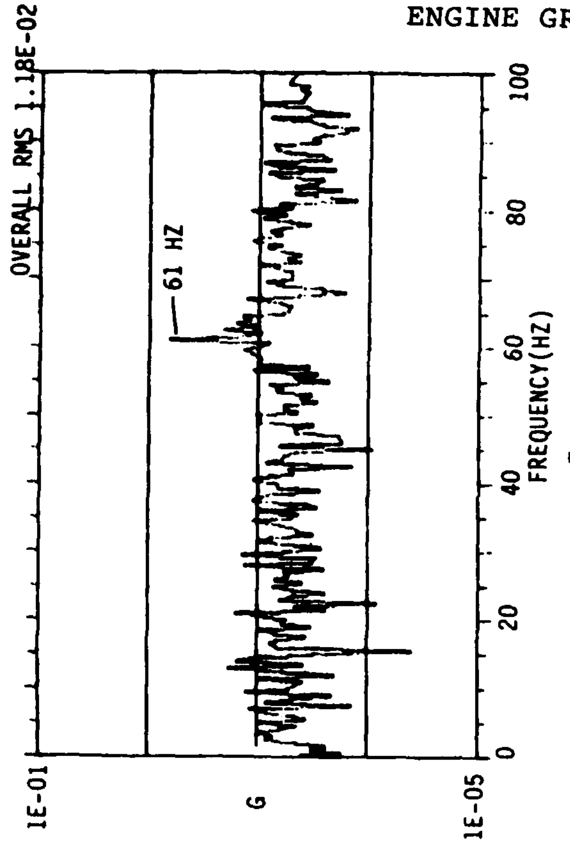
A/C 306 Rumble F

APPENDIX F

GROUND TEST DATA FOR A/C 120 and 306

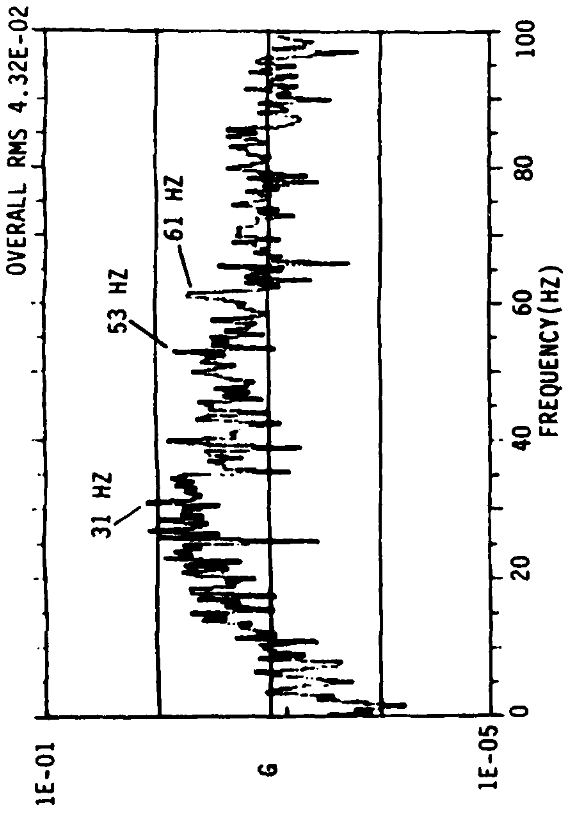
A/C 120

ENGINE GROUND RUN DATA

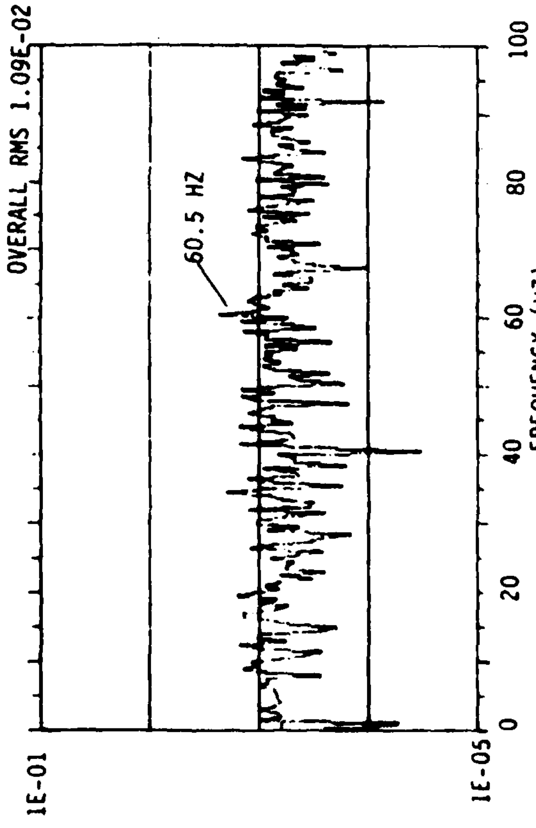


Engine 2

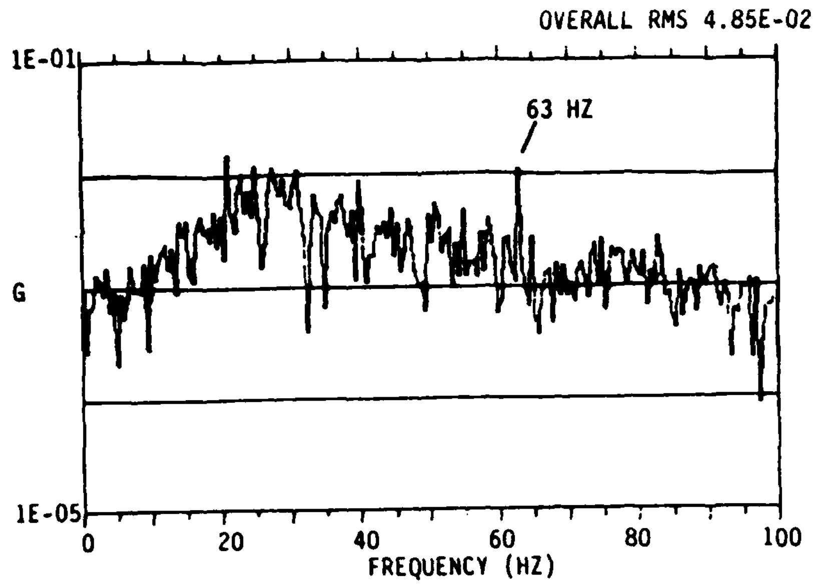
A/C 120 N1 41%



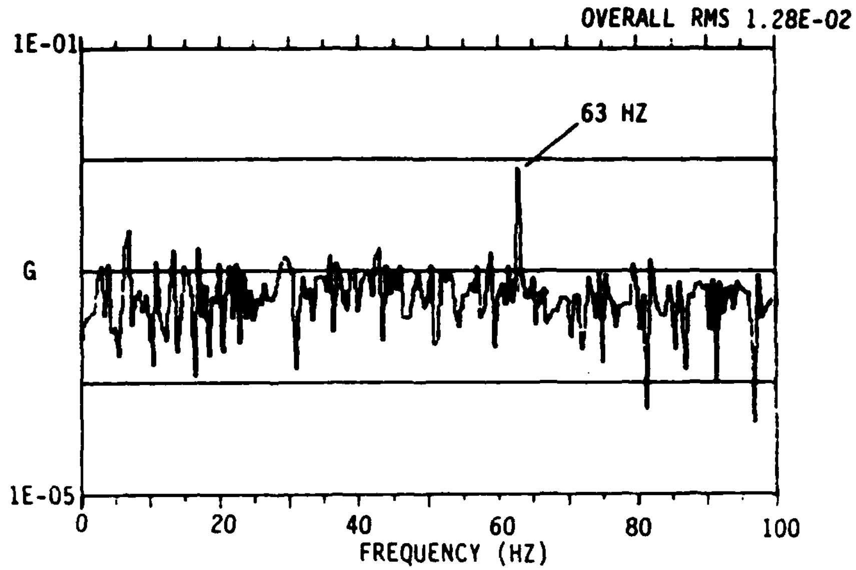
Nav Station



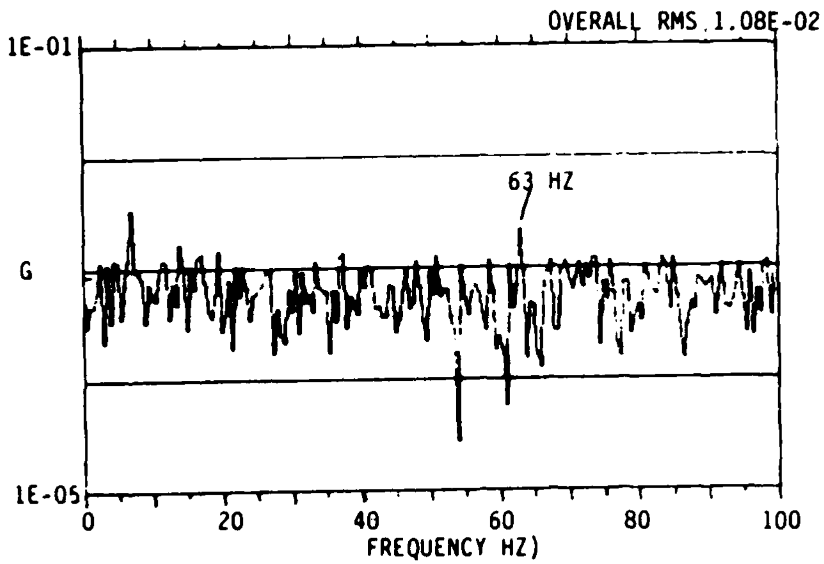
Engine 3



Nav Station

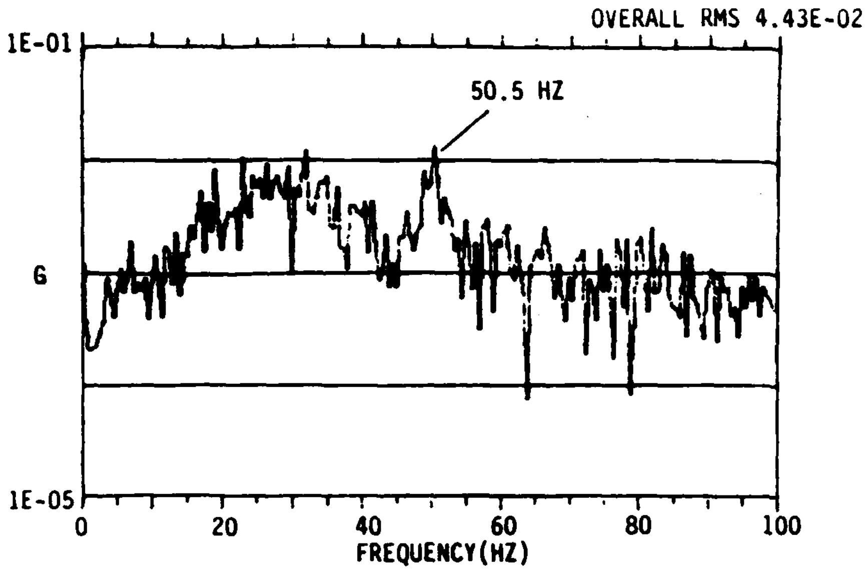


Engine 2

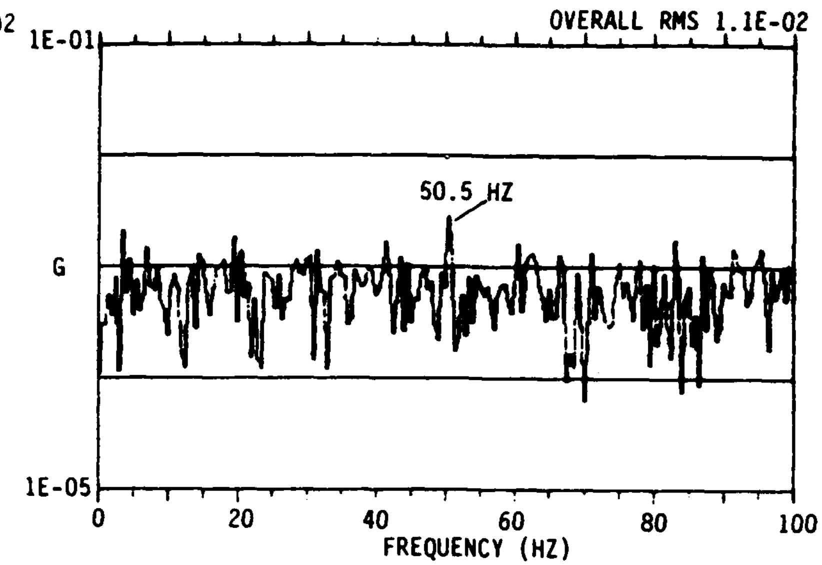


Engine 3

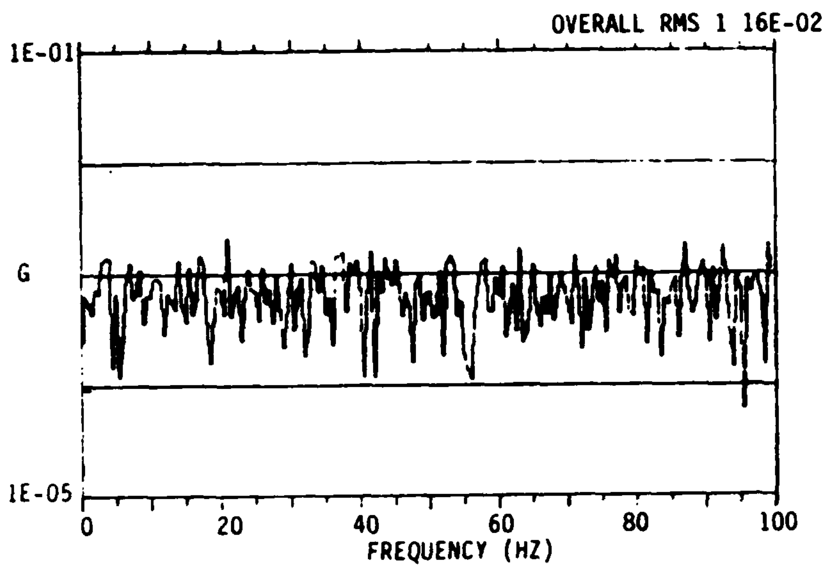
A/C 120 N1 73%



Nav Station



Engine 2

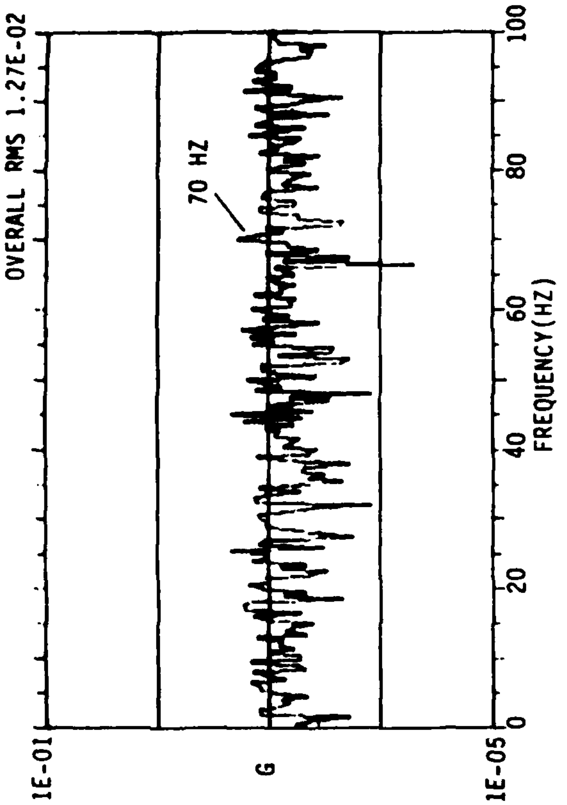


Engine 3

A/C 120 Decelerating

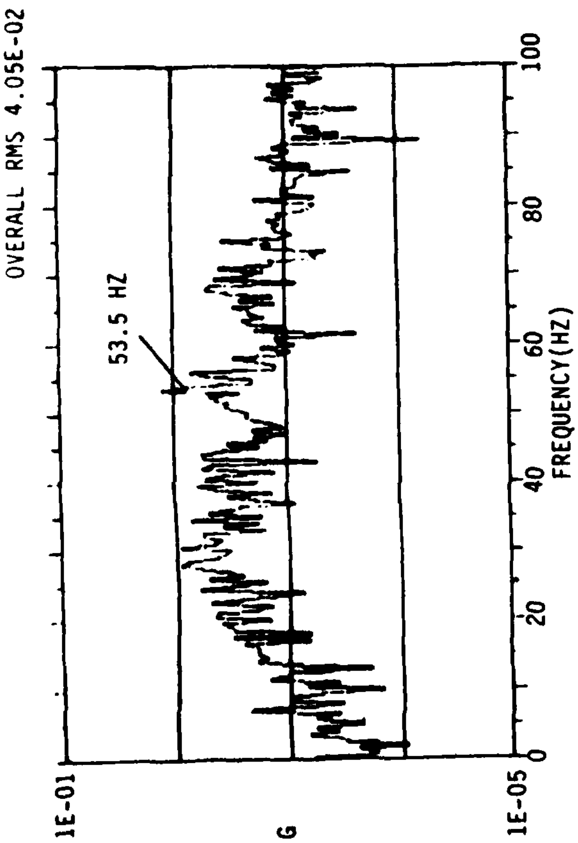
A/C 306

ENGINE GROUND RUN DATA

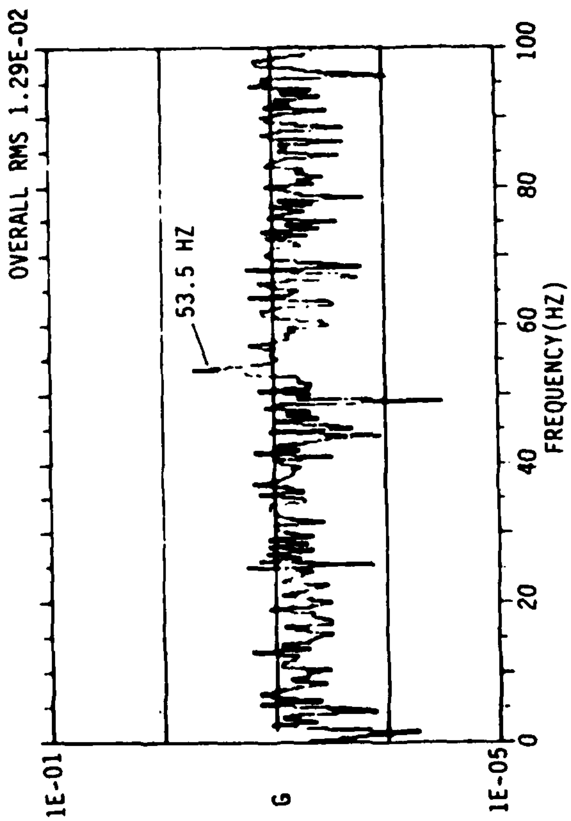


Engine 2

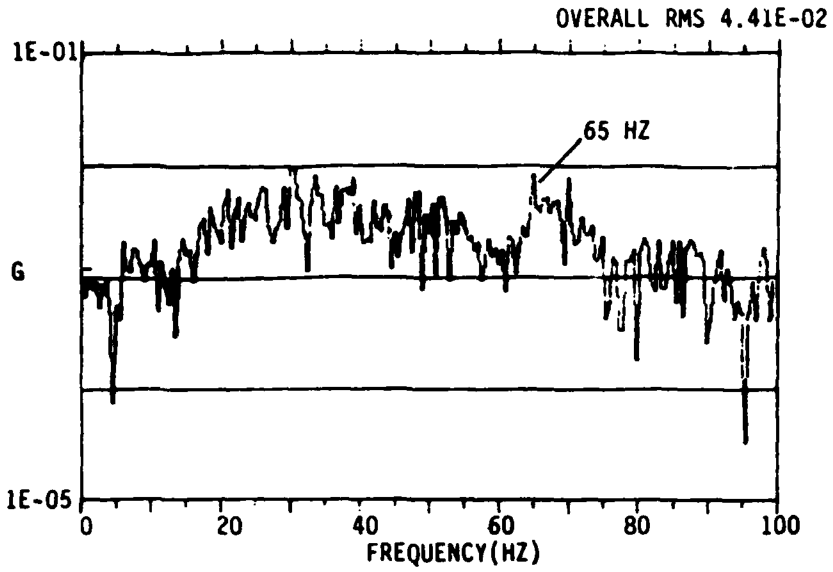
A/C 306 N1 52%



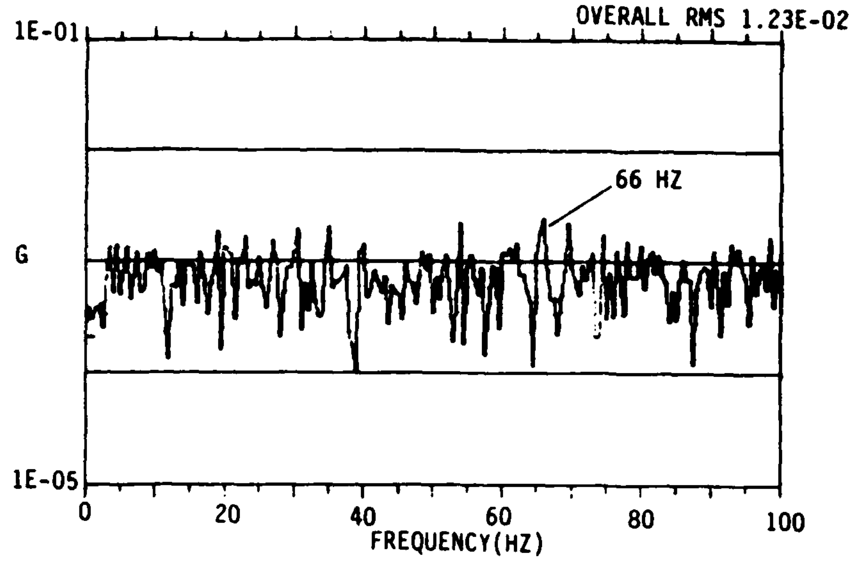
Nav Station



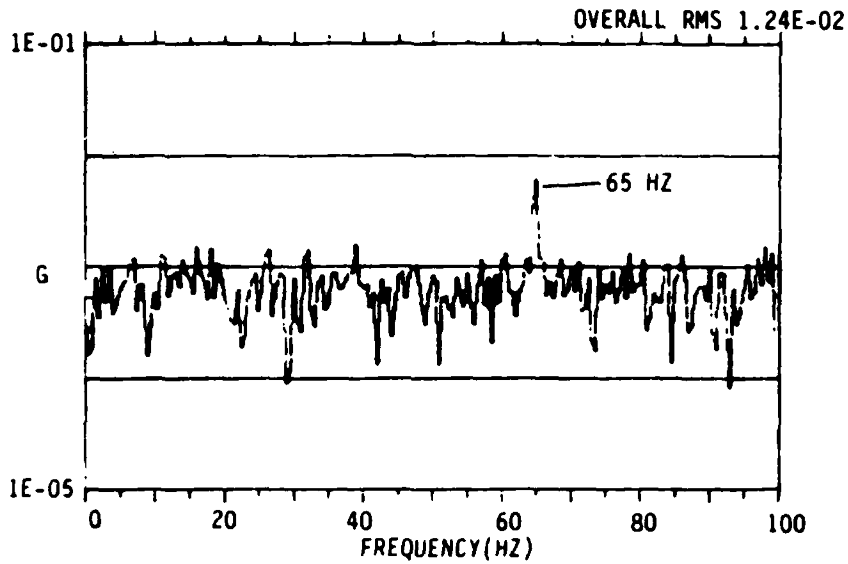
Engine 3



Nav Station

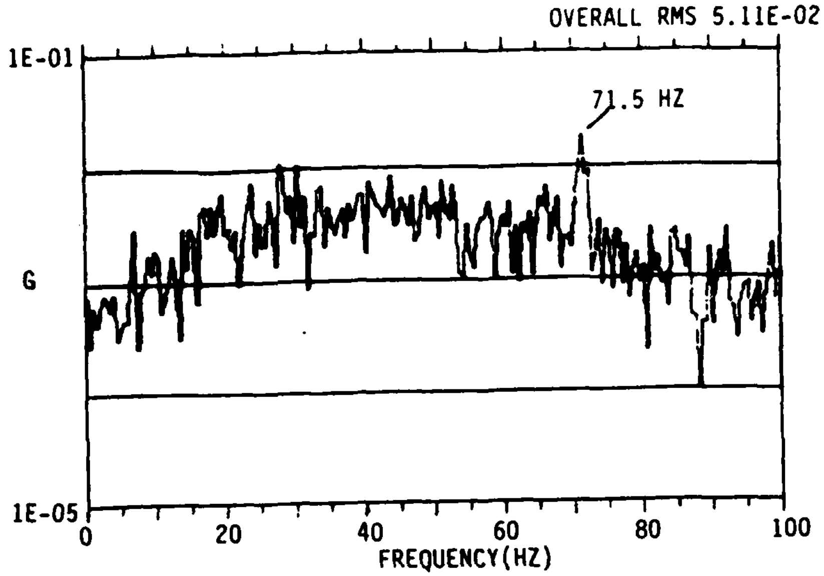


Engine 2

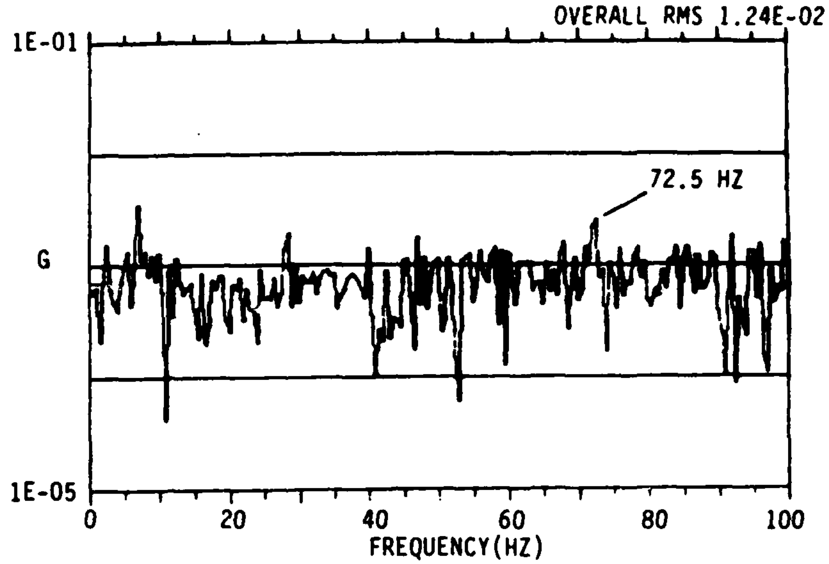


Engine 3

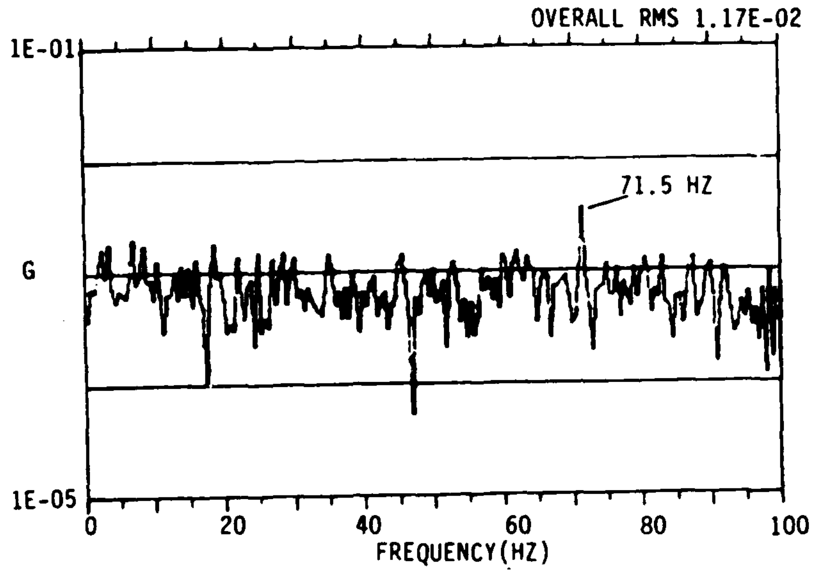
A/C 306 N1 78%



Nav Station

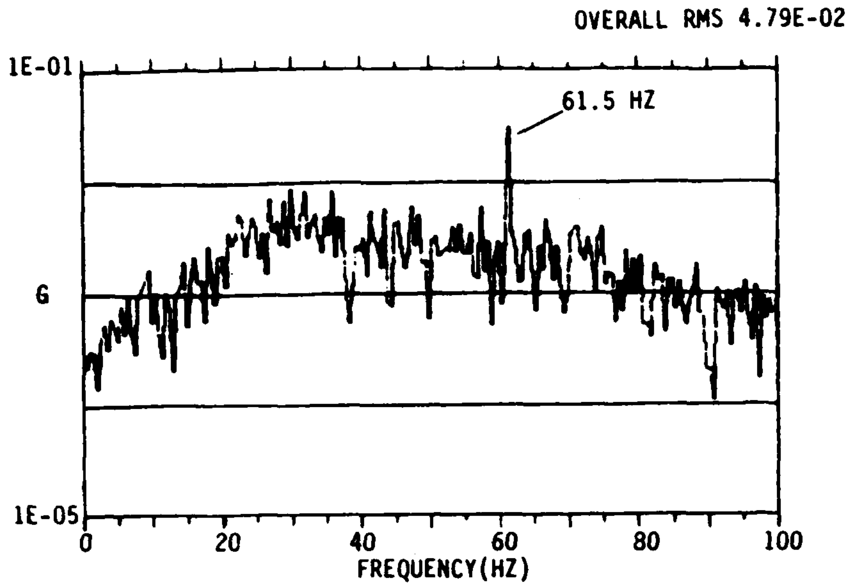


Engine 2

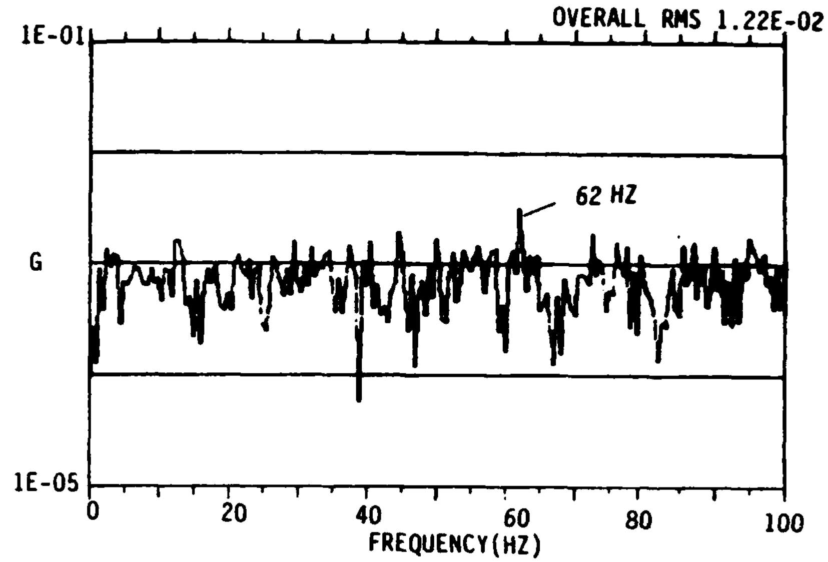


Engine 3

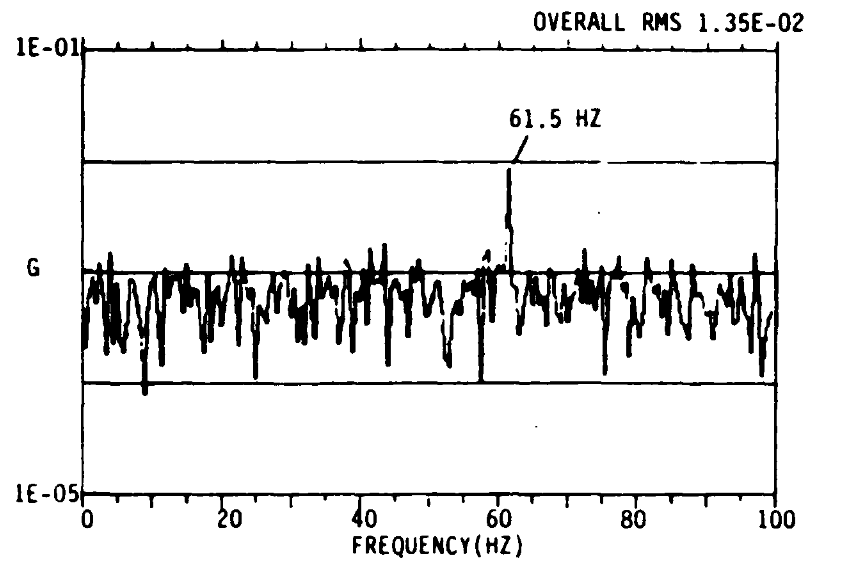
A/C 306 N1 84%



Nav Station



Engine 2



Engine 3

A/C 306 Decelerating

*U.S.Government Printing Office: 1989 — 648-056/04259

END
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